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C-CORE

Technical Report

HF Radar Technology Transfer Project-Evaluation Phase

Kenneth A. Butt
Philip K. Jeans

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C-CORE

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The Centre for Cold Ocean Resources Engineering (C-CORE) was established at Memorial University of Newfoundland in St. John's in 1975. Its initial funding was provided by the Devonian Group of Charitable Foundations of Calgary. This support is being supplemented by grants from governments and industry.

The Centre's mandate is to undertake research that will assist the safe and orderly development of Canada's resources in which cold and ice frequented oceans are a problem. C-CORE's main concentration of research is on ice, its properties, detection and behaviour.

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Abstract

A high frequency surface wave radar system known as Coastal Ocean Dynamics Applications Radar (CODAR) is examined for potential application to Canadian ocean resources engineering. The system, as developed by the National Oceanic and Atmospheric Administration (NOAA) is capable of mapping large area (60 x 60 km) surface currents remotely from a land base in near real time. A functional description including the system's novel phase measuring technique applied in combination with modern computer technology to direction finding is provided.

CODAR is described as an appropriate foundation on which to begin Canadian development of HF surface wave radar systems. A technology transfer program is outlined with potential application to operational floating ice related problems.

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1.0 INTRODUCTION

Canada, as a country, accepted new and wider responsibilities when it made its territorial claim of a 200 mile limit for its coastal waters. One of these responsibilities is to develop this resource. The immediate precursor to any development is to gather knowledge for the environmental description and the resource potential of these waters.

An effective remote sensing capability is one route for an efficient collecting of the necessary data and a land based remote sensing capability is the route for data collection from the often fogbound and stormbound ocean region of eastern Canada.

Recently a new remote sensing system called Coastal Ocean Dynamics Application Radar (CODAR) has been developed for measuring ocean surface currents through Doppler processing of the high frequency (HF) surface wave backscatter from the ocean surface. Although CODAR has been primarily a National Oceanic Atmospheric Administration (NOAA) development, the overall work on this technique to date has taken place in many international government and university laboratories (Barrick and Evans, 1976; Trizna et al, 1977; Shearman et al, 1979; SRI International, 1980).

C-CORE through its commitment to the development of Canadian cold ocean resources has recently initiated a program to acquire CODAR technology. The centre's intention is to develope this technology further to meet Canada's special needs for remote detection; both for ice and ocean environmental hazards.

The operational capability of CODAR is spatial mapping of ocean surface current vectors and repetitive mapping in a temporal sense. This is a unique capability which is not available through any of the conventional

oceanographic techniques. A short list of potential applications of CODAR are: (i) routine environmental measurements to quantify coastal processes, (ii) the ability to directly monitor surface transport in the case of an oil spill accident, (iii) a potential tool to study ice and iceberg behaviour and (iv) remote surface drift measurement to support search and rescue.

This report deals primarily with the evaluation phase of the project with a detailed description of the radar and an up-to-date summary of the international state-of-the-art. The major topics in the development and the proposed funding scheme are included.

1.1 HF Radar for Oceanographic Measurement

HF radar (CODAR) utilizes the 6 metre ocean wavelength which is one-half the electrical wavelength of the transmitted signal as a resonant structure satisfying the Bragg (first order) equation for scattering (Crombie, 1955). For any given ocean wavelength, the phase velocity of the approaching and receding wave is unique and can be analytically determined. Since Doppler frequency shift is a measure of velocity, it therefore can be shown that the Doppler frequency of the first order sea echo response is a measure of the phase velocity of the 6 metre ocean wave. The transmitted wavelength is well defined, therefore we can calculate the expected Doppler shift of the first order backscatter and thus postulate that any difference in the measured first-order Doppler shift is a measure of the component of near-surface currents flowing radial to the radar antenna. The mathematical equation describing the velocity of the radial surface current component is given by:

$$V_r = \frac{C}{2 f_o} \left(f_A^{(+)} - f_E^{(+)} \right)$$

where V_r = radial current velocity in metres/sec.

C = free space EM propagation velocity in metres/sec.

f_o = radar frequency in Hertz

$f_A^{(+)}$ = positive component* of the actual Doppler frequency shift of the radial received signal in Hertz

$f_E^{(+)}$ = positive component* of the expected Doppler frequency shift due to 1st order Bragg diffraction in Hertz

* In practice, f_A & f_E are derived from an average of both the positive and negative components of the complex Doppler spectrum.

A more complete discussion of this relationship is given by Barrick et. al. (1977) where the term $(f_A^{(+)} - f_E^{(+)})$ is given as Δf.

The ease with which this measurement can be made using surface wave propagation is in direct contrast to similar techniques utilizing the ionosphere for extended range through reflection/refraction where the backscatter Doppler information has been contaminated by uncertain ionospheric movements.

1.2 International Research Activity

HF radars have been engineered and tested over the years by many countries. Investigators in Britain, France, West Germany, and Australia are also experimenting with the concept. Although the topic is not new, lack of support technology and established priorities with existing microwave radar have tended to impede progress in producing "turn-key" HF radar systems.

However, work is still ongoing, with recent advances in high speed computer technology having reduced most of the barriers to application systems. An article in New Scientist (October 23, 1980) entitled "Radar keeps aircraft

on the straight and narrow" indicates a potential British development for long-range aircraft zone control radar. A more recent edition of the same journal (February 5, 1981) describes an HF ground wave radar marketed by Syminex, a French company. The system, although still rudimentary in engineering and development will perform oceanographic measurements similar to CODAR.

A discussion in March of this year with Dr. Florian Shirmer of the University of Hamburg produced an outline of recent West German activity in HF radar under the leadership of Dr. K. Hasselmann. They are purchasing a complete two site NOAA CODAR system and plan to be operational by the fall of 1981 to run a data collection program in the North Sea. They intend to carry out ice detection experiments in the West German Antarctic in the summer of 1982.

It is clear that as such developments progress internationally, the need for Canadian participation will increase if we intend to play a role in the area of ocean systems management; particularly as it relates to Arctic transportation and offshore exploration.

1.3 Inherent Advantages of the CODAR System

The two initial considerations for specifying any radar system are frequency and carrier modulation. For application to ocean mapping it is important that the wavelength selected will resonate at first order with a corresponding ocean wave as previously discussed. Since this corresponds primarily to wavelengths from 150 m to 5 m, therefore for a one-half radar wavelength relationship we are looking at radio frequencies in the MF/HF band from 1 MHz to 30 MHz. Some thought has been given to operation at

VHF, however a severe reduction in range is anticipated. Some preliminary work evaluating surface wave radar potential for mapping ocean variables has used existing LORAN A navigational sites (Shearman et. al., 1979). The low ground wave attenuation associated with the 1.95 MHz radio frequency afforded potential coverage to 300 km in range. However, the long wavelength (therefore, long antennas) precludes the application of such systems in a portable sense; especially for current mapping, where two spatially separated radars are needed to unambiguously derive each cell vector, to be discussed below.

The 25 MHz frequency selected for the CODAR system is a tradeoff between the lower surface wave attenuation available at lower frequencies and the portability afforded by shorter wavelengths. This tradeoff is not as severe as might be first expected. The longer ocean waves needed to satisfy the Bragg resonant backscatter condition often have smaller amplitudes and hence scatter less radar energy and result in reducing the effective range. The shorter ocean wavelengths (in this case, 6 m) are present most of the time and will normally be fully developed for water depths greater than 2 m. The frequency selection also represents a compromise between the low noise environment afforded at very-high frequencies and the increased noise levels at the lower end of the HF band.

There still remains the important regulatory issue of frequency allocation to meet "World Spectrum" specifications. At the moment CODAR frequencies fall in an area allocated for maritime mobile, fixed mobile and radio astronomy. Investigation into the use of the maritime mobile frequency band is presently underway. It is also possible that a lower frequency could be specified for

CODAR to a band slot with less radio traffic. This would only represent a slightly increased cost for such modifications.

CODAR uses a "pulsed" rather than a "swept frequency" (FMCW) carrier modulation scheme. Both of these schemes employ a very narrowband final stage, phase coherent receiver design. The narrower front end afforded by FMCW primarily achieves out-of-band narrowband noise rejection. This clearly provides better instantaneous signal measurements in the presence of noise but is not a significant improvement for coherent processing unless by the improbable event the noise signal is phase locked to the radar reference oscillator for a major portion of the processing time. Of course a major advantage of the application of FMCW to surface wave radar is the narrower bandwidth needed for transmission.

A major disadvantage of FMCW in a CODAR-like application arises because both receiver and transmitter are always on. Poor isolation between the CODAR transmit and receive antennas would require that they be separated by distances greater than line of sight in order to prevent overdriving the high sensitivity receiver, a limitation unacceptable for a portable HF radar system. There are also problems associated with range-range rate ambiguity and application of range gain on FMCW systems including the latest designs in psuedo randomly chopped monostatic FMCW. These problems are not encountered with pulsed systems and therefore the engineering costs are lower.

The brief review of the open international research activity and comparison of available technologies indicates that the CODAR system is the most suited for our purposes and hence the logical place to begin a development program for the application of HF surface wave radar to ocean engineering and offshore management systems.

2.0 CODAR SYSTEM DESCRIPTION

State-of-the-art HF surface wave radar systems are presently only available through the Environmental Research Laboratories of NOAA and a company called CODAR Technology Inc., both of Boulder, Colorado, U.S.A. The system known as Coastal Ocean Dynamics Radar (CODAR) operates between 25.0 and 26.0 MHz and has demonstrated an ability to map ocean surface currents within a 60 km range in near real-time (Evans and Georges, 1979).

The following briefly lists the present capabilities of a CODAR current mapping radar:

Map resolution	-	1.2 km X 1.2 km
Approximate map size	-	60 km X 60 km
Maximum range	-	76 km
Demonstrated range	-	60 km
Maximum velocity	-	Greater than 3 m/sec
Measurements proved possible	-	Wind driven surface currents over 36 minute average to $\pm$ 10 cm/sec.
	-	Tidal components over 24 to 36 hour with least squares analysis to $\pm$ 5 cm/sec
	-	Trajectory prediction from consecutive 36 minute data sets to $\pm$ 1 cm/sec over 24 hours.

The theoretical limits of the present system based upon a 8192 point time series yields current velocity measurements to $\pm$ 0.6 cm/sec. The hardware noise limits indicate measurement capabilities to 0.1 cm/sec. However, it is not reasonable to assume that the currents have remained stable over the 36 minutes necessary to collect the complete time series. In drifter comparison experiments the accuracy has been better than $\pm$ 10 cm/sec. It should be noted that this error could be a reflection of uncertainties in drifter motion.

Some of the above information was obtained from sources that cannot be formally referenced at this time. However, more detail commentary is provided as discussion by Dr. Don Barrick in the "Verbatim Transcript of C-CORE HF Radar Seminar at Memorial University of Newfoundland" (Appendix A).

The physical principle adapted for producing a map of current vectors representing surface water transport is based upon the Bragg scattering of radio waves produced by ocean waves (see section 1.1). The basic principle is that there is a resulting Doppler frequency shift induced on a radar return by a sea target. This shift is due only to the relative velocity of one particular ocean wave with respect to the radar. Thus one radar station can only measure the component of the total velocity vector that is either directly toward or directly away from the radar. Two radars that are physically separated are required to describe the complete vector. The two components of the vector are combined using vector addition in one of the final steps in the data interpretation software of a high speed field computer system. When the radar data is processed at the measurement station the vector components from one site are transferred to the other site automatically using a VHF telemetry link. The complete current vector map can then be drawn on a high speed incremental plotter in the field or stored for latter analysis.

The three basic quantities that are measured at each station are;

1. The range to the target.
2. The azimuthal angle to the target.
3. The radial velocity component of the target.

The target in terms of a current mapping radar is a patch of ocean which under commonly used radar terminology would be called noise or sea clutter.

The target could also be a transponder or what might be considered a more conventional target; a ship or an iceberg. The type of target is resolved by the spectral content of its return. Land or a non-moving target would show up as a zero Doppler shift return and would be ignored.

A CODAR current mapping system requires two complete radar stations. Located some tens of kilometres apart, the absolute spacing is dictated by the physical constraints of the site selected and available transmit power. The optimization of site spacing is discussed by Barrick and Evans (1976). A typical spacing would be about 35 km. The resulting area of sea coverage would then be about 2500 square km when operating on a coastline with 180^{o} of ocean. When the site has 360^{o} of ocean the coverage would be somewhat less then 5000 square km because of the reduction in the transmission antenna gain in going from a directional to an omnidirectional configuration. While a typical range of 60 km would be achieved under favourable conditions this could under extreme conditions drop down to 45 km for the same site depending on sea-state and r.f. noise background (Appendix A).

The system automatically calculates the signal to noise ratio of the radar returns and will reject any noise distorted measurements. Thus any dramatic reduction in maximum range will just be reflected in rejection of the outlying vectors on the current vector map. This accounts for the irregular shape of some vector maps presented in the literature. Severe reduction in range is uncommon and is seldom persistent (Appendix A).

The range to the target is determined by the classical radar technique of measuring travel time to the target (i.e. sampling at the end of the two-way propogation time of the signal). The distance can then be calculated using the known velocity of the signal in free-space.

The absolute maximum range is 76 km based on the pulse repetition frequency (PRF) of the radar set. The range resolution can be 1.2 or 2.4 km based on an operator selectable pulse width of 8 or 16 microseconds. This results in a grid of current vectors spaced 1.2 or 2.4 km apart.

The transmitter antenna is either completely omnidirectional or for the case of a directional Yagi antenna it can be assumed to radiate equally in the required area of sea coverage. The receiver antenna array consists of four whip antennas located on the corners of a square. Each one is connected to the receiver sequentially. It is an omnidirectional receiving array and therefore collects the signal from the entire circular coverage at any one instant of time. Time (range) gating of course reduces information to an equivalent ring whose width is ultimately dictated by the transmitted pulse width. Thus for an 8 microsecond pulse information would be available from 1.2 km wide rings around one radar station.

In the present NOAA setup for mapping currents both radars are operated simultaneously at the same frequency. This is done to conserve bandwidth in the widely used HF region. Each radar will be detectable to some degree on the video output of the other radar if both are run at the same frequency but this information will be filtered out by the narrowband effect of the signal due to slight variations in the two reference oscillators. Even though the oscillators of the radar sets are extremely stable, the 2 Hz signal processing bandwidth is enough to reject the signal from the other radar. The other radar may drift thru this bandwidth limited window but its effect will be averaged out by a time series of any reasonable length.

The present system does not have the capability to compensate for any motion of the antennas. The basic measurement of the radar system are the Doppler frequency shifts of the radar carrier due to the relative velocity

of the targets with respect to the radar station. Unknown antenna motion would distort the Doppler spectrum and introduce error into the wavefield measurement. Research currently being conducted by NOAA indicates that if this is a problem then the antenna motion could be automatically measured and its effects could be removed. This may be necessary for both fixed and semi-submersible offshore platforms. These platforms may not move much in low or normal sea states but the motion induced by heavy seas may cause significant contamination of the Doppler spectrum. Platform motion may be eliminated or reduced to a tolerable level in the software signal processing stage. However it is expected that additional hardware modifications would be necessary for the installation aboard a ship that travels at any appreciable speed. It would be necessary to beat the return signal to a non-zero baseband corresponding to the ship's velocity. Due to the narrow frequency passband of the receiver output, this compensation would have to be performed in the radar before the final IF stage mixing.

2.1 The Four Element Array

The wavelength used by CODAR is approximately 12 metres. To overcome the problem of large antenna size needed for a narrow beam scanner, four 1/4 λ radially arranged vertical antennas are used to detect the phase of the returning radar signal. This approach forced the development of special algorithms to transform phase into azimuthal information and hence the heavy dependence upon the latest developments in computer technology to allow real-time implementation of the calculation process.

No beam steering has been performed up to the time that the data has been received by the computer. No amplitude weighting has been applied to

the elements for any particular direction. The angle finding is based on resolution in frequency rather than resolution of amplitude. Thus the angle resolution is based solely on the signal to noise ratio of the received return and not on the physical spacing of the elements provided that the system timing (for all practical purposes) can be assumed ideal. This is quite a significant departure from the classical radar operation. It is made possible by the nature of the target. Each patch of sea ocean will have a radial component of velocity toward one radar station. This will correspond to a particular Doppler frequency recovered from the spectrum of the sampled antenna time series. Another patch of ocean with a different radial velocity will correspond to another frequency. Both patches may have the same current velocity but because of the relative location of the radar, each will result in a different radial component.

The four elements arranged in the square can resolve two angles of arrival over 360^{o}. The diagonal of the square must be slightly less than one half of the radar wavelength to prevent phase ambiguity in the angle-of-arrival algorithm for expected noise levels (Appendix A). However, inspection of the algorithm (section 2.2) indicates that for a fixed angular resolution, the antenna spacing can be made smaller. This observation will be investigated further if antenna spacing becomes critical for real-time implementation in the field. The processing can detect the condition where there are three equal signals at different angles of arrival over 360^{o} but must subsequently reject this measurement point in the Doppler spectrum. It can be theoretically shown that any number of directions of arrival can be resolved for each Doppler frequency if enough elements are used. However this would lead to very complex cal-

culations that would be cumbersome for real time operation in the field. Basically a simultaneous set of equations equal in number to the number of elements has to be solved. It has been found that even for a fairly complex current field rarely will more than two different sample patches give the same radial velocity at the same radial range. NOAA has collected over 9000 data tapes using CODAR in 10 different sites and has found that resolution of two angles is sufficient. The algorithm of this angle finding routine is discussed in the following section.

2.2 The Four Element Solution

The direction finding technique of the CODAR system consists of a four element phase measuring antenna array used in conjunction with a direction finding algorithm implemented in computer software. This section will present the azimuthal angle finding algorithm in some detail because of its complexity and central importance to the operation of a CODAR system. A detailed description of the physical layout of the receiving antenna array was presented in the preceeding section.

The four omnidirectional receiving elements operate sequentially and otherwise independently. Each one is connected to the radar receiver for a single scan period in turn. The remaining three antennas are disconnected and do not contribute to the receiving pattern during this time. The net result is that the receiving array is also omnidirectional. Even though the transmitting antenna and the receiving antenna array are physically separated by tens of meters, the direction finding azimuth resolution does not depend on the spacing or orientation of the transmitter antenna from the receiver "phase measuring array". The direction finding technique assumes a monostatic radar operation.

The operation of four element array is illustrated in figure 1. Two signals of arbitrary amplitude, phase and angle of arrival are depicted. These two signals are at the same Doppler frequency i.e. two signals are assumed. The algorithm is labelled the ("FOUR - ELEMENT SOLUTION") and the set of formula are depicted in figure 2. The symbols used in these two figures are;

$\overset{o}{A_1} = A_1 \angle \beta_1$

= amplitude and phase of signal #1 (the phase angle (β) is measured in radians relative to the center of the receiving array)

α_1 = angle of arrival of signal #1 as shown in figure 1.

$\overset{o}{A_2} = A_2 \angle \beta_2$

= amplitude and phase of signal #2 (the phase angle (β)is measured in radians relative to the center of the receiving array) in radians.

α_2 = angle of arrival of signal #2 as shown in figure 1.

$\overset{o}{V_A}$ = Complex voltage (digitized) corresponding to one Doppler frequency from the spectra of antenna A for one range gate.

$\overset{o}{V_B}$ = Complex voltage (digitized) corresponding to one Doppler frequency from the spectra of antenna B for the same range cell as V_A.

$\overset{o}{V_C}$ = Complex voltage (digitized) corresponding to one Doppler frequency from the spectra of antenna C for the same range cell as V_A.

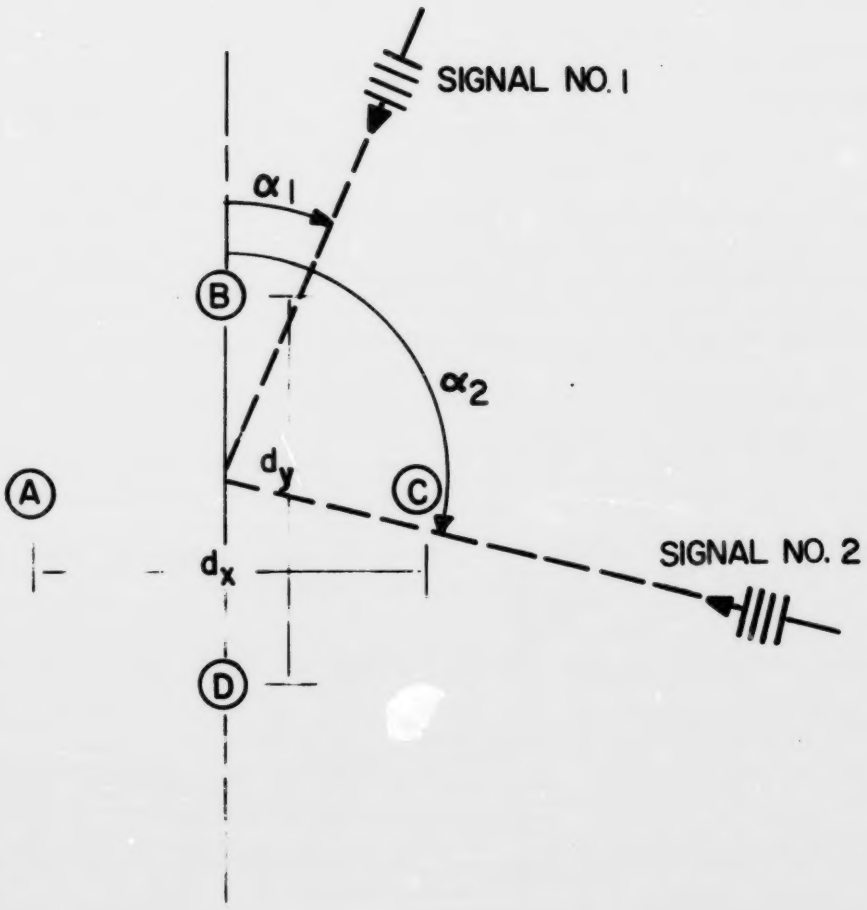

Figure 1. FOUR ELEMENT ARRAY RECEIVING ANTENNA

Illustrated is the case of two signals arriving with the same doppler shift but at two different angles of arrival α_1, and α_2 over 360^o of space.

$\overset{o}{V}_D$ = Complex voltage (digitized) corresponding to one Doppler frequency from the spectra of antenna D for the same range cell as V_A.

K_o = wavenumber

$= 2\pi / \lambda$

λ = wavelength of the radar

dx = spacing between antenna A and antenna C (in wavelengths)

dy = spacing between antenna B and antenna D (in wavelengths)

$K_o\, dx = K_o\, dy = \pi$ when $dx = dy = \lambda/2$ for exact antenna spacing

$\overset{o}{\zeta}_x, \overset{o}{\zeta}_y, \overset{o}{\psi}_x, \overset{o}{\psi}_y, \overset{o}{\eta}_1, \overset{o}{\eta}_2, \overset{o}{\xi}_1, \overset{o}{\xi}_2, \overset{o}{x}_1, \overset{o}{x}_2, \overset{o}{y}_1, \overset{o}{y}_2$, are intermediate terms used in the calculations that can be assumed to have no physical significance for the purposes of this discussion.

o = symbol for a vector (as used by Barrick in C-CORE Seminar, Appendix A)

* = complex conjugate

Equations (i), (ii), (iii), (iv) and (v) refer to figure 2.

Thus the four inputs to the four - element solution are;

$$\overset{o}{V}_A, \quad \overset{o}{V}_B, \quad \overset{o}{V}_C, \quad \overset{o}{V}_D$$

The outputs are;

$$\overset{o}{A}_1 \; @ \; \alpha_1 = A_1 \angle \beta_1 \; @ \; \alpha_1$$

$$\overset{o}{A}_2 \; @ \; \alpha_2 = A_2 \angle \beta_2 \; @ \; \alpha_2$$

The algorithm consists of two sets of "mirrored equations". It is a closed form solution to a set of four simultaneous equations. The

FOUR-ELEMENT SOLUTION

$$\begin{pmatrix} \overset{o}{\zeta}_y \\ \overset{o}{\psi}_y \end{pmatrix} = \frac{\begin{pmatrix} \overset{o}{V}_D^* & -\overset{o}{V}_B \\ -\overset{o}{V}_B^* & \overset{o}{V}_D \end{pmatrix}\begin{pmatrix} \overset{o}{V}_A \\ \overset{o}{V}_C^* \end{pmatrix}}{(V_D^2 - V_B^2)} \quad \text{(i)} \qquad ; \qquad \begin{pmatrix} \overset{o}{\zeta}_x \\ \overset{o}{\psi}_x \end{pmatrix} = \frac{\begin{pmatrix} \overset{o}{V}_A^* & -\overset{o}{V}_C \\ -\overset{o}{V}_C^* & \overset{o}{V}_A \end{pmatrix}\begin{pmatrix} \overset{o}{V}_D \\ \overset{o}{V}_B^* \end{pmatrix}}{(V_A^2 - V_C^2)} \quad \text{(ii)}$$

$$\overset{o}{y}_{1,2} \equiv e^{ik_o dy \cos\alpha_{1,2}} = \frac{(1-\zeta_y^2-\psi_y^2) \pm \sqrt{(1-\zeta_y^2-\psi_y^2)^2 - 4\zeta_y^2\psi_y^2}}{2\overset{o}{\zeta}_y\overset{o}{\psi}_y^*} \equiv \eta_{1,2}^2 \quad \text{(iii)}$$

$$\overset{o}{x}_{1,2} \equiv e^{ik_o dx \sin\alpha_{1,2}} = \frac{(1-\zeta_x^2-\psi_x^2) \pm \sqrt{(1-\zeta_x^2-\psi_x^2)^2 - 4\zeta_x^2\psi_x^2}}{2\overset{o}{\zeta}_x\overset{o}{\psi}_x^*} \equiv \xi_{1,2}^2 \quad \text{(iv)}$$

$$\begin{pmatrix} \overset{o}{A}_1 \\ \overset{o}{A}_2 \end{pmatrix} = \frac{\begin{pmatrix} \overset{o}{\xi}_2^* & -\overset{o}{\xi}_2 \\ -\overset{o}{\xi}_1^* & \overset{o}{\xi}_1 \end{pmatrix}\begin{pmatrix} \overset{o}{V}_A \\ \overset{o}{V}_C \end{pmatrix}}{(\overset{o}{\xi}_1\overset{o}{\xi}_2^* - \overset{o}{\xi}_1^*\overset{o}{\xi}_2)} = \frac{\begin{pmatrix} \overset{o}{\eta}_2^* & -\overset{o}{\eta}_2 \\ -\overset{o}{\eta}_1^* & \overset{o}{\eta}_1 \end{pmatrix}\begin{pmatrix} \overset{o}{V}_D \\ \overset{o}{V}_B \end{pmatrix}}{(\overset{o}{\eta}_1\overset{o}{\eta}_2^* - \overset{o}{\eta}_1^*\overset{o}{\eta}_2)} \quad \text{(v)}$$

Figure 2

reason for the two equations is that the angle of arrival is calculated from both the sine and cosine of the angle. Thus for α_1 the following two values are obtained first;

sine α_1 - from equation (iv) (the mirror of (iii))

cosine α_1 - from equation (iii) (the mirror of (iv))

Then α_1 is calculated using the special ATAN2 function, where ATAN2 is the arc tangent as defined within the limits of the computer's precision.

$$\alpha_1 = \text{ATAN2} \left(\frac{\text{sine } \alpha_1}{\text{cosine } \alpha_1} \right)$$

The ATAN2 function will resolve an ambiguity that would occur if only the sine α_1 or the cosine α_1 were used to calculate α_1. For example if the sine $\alpha_1 = 0.292$ then arcsine 0.292 would give $\alpha_1 = 17^o$ but the sine 163^o would also give 0.292. Similiarly if cosine $\alpha_1 = 0.956$ then this could mean that $\alpha_1 = 17^o$ or -17^o. Using the ATAN2 function there is only the single answer $\alpha_1 = 17^o$.

The following is the step by step method of the sequence used in obtaining two signals and their direction from the algorithm.

1. $\overset{o}{\zeta}_y$ and $\overset{o}{\psi}_y$ are calculated from equation (i) using the four inputs $\overset{o}{V}_A$, $\overset{o}{V}_B$, $\overset{o}{V}_C$ and $\overset{o}{V}_D$.

2. $\overset{o}{\zeta}_x$ and $\overset{o}{\psi}_x$ are calculated from equation (ii) using the four inputs $\overset{o}{V}_A$, $\overset{o}{V}_B$, $\overset{o}{V}_C$ and $\overset{o}{V}_D$.

3. $\overset{o}{\eta}\,\overset{2}{}_1$ is calculated from equation (iii) using $\overset{o}{\zeta}_y$, $\overset{o}{\psi}_y$ and a"+"sign in the numerator.

4. cosine α_1 is calculated from equation (iii) using $\overset{o}{\eta}\,\overset{2}{}_1$.

Note: Euler's equation states

$$e^{\pm i\theta} = \text{cosine } \theta + i \text{ sine } \theta \text{ where } i = \sqrt{-1}$$

thus $$e^{i K_o \, dy \text{ cosine } \alpha_1} = \overset{o}{\eta}\,\overset{2}{}_1$$

$$= \text{Re} \left\{ \overset{o}{\eta}\,\overset{2}{}_1 \right\} + i \, \text{Im} \left\{ \overset{o}{\eta}\,\overset{2}{}_1 \right\}$$

then $$K_o \, dy \text{ cosine } \alpha_1 = \text{arcosine} \left(\text{Re} \left\{ \overset{o}{\eta}\,\overset{2}{}_1 \right\} \right)$$

$$\text{cosine } \alpha_1 = \frac{\text{arcosine} \left(\text{Re} \left\{ \overset{o}{\eta}\,\overset{2}{}_1 \right\} \right)}{K_o \, dy}$$

5. $\overset{o}{\eta}\,\overset{2}{}_2$ is calculated from equation (iii) using $\overset{o}{\zeta}_y$, ψ_y and a"-"sign in the numerator.

6. Cosine α_2 is calculated from equation (iii) using $\overset{o}{\eta}\,\overset{2}{}_2$.

7. $\overset{o}{\xi}\,\overset{2}{}_1$ is calculated from equation (iv) using $\overset{o}{\zeta}_x$, $\overset{o}{\psi}_x$ and a"+"sign in the numerator.

8. Sine α_1 is calculated from equation (iv) using $\overset{o}{\xi}\,\overset{2}{}_1$.

9. $\overset{o\ 2}{\xi_2}$ is calculated from equation (iv) using $\overset{o}{\zeta_x}$, $\overset{o}{\psi_x}$ and a"-"sign in the numerator.

10. sine α_2 is calculated from equation (iv) using $\overset{o\ 2}{\xi_2}$.

11. α_1 is calculated from the ATAN2 function using sine α_1 and cosine α_1.

12. α_2 is calculated from the ATAN2 function using sine α_2 and cosine α_2.

13. $\overset{o}{\eta_1}$ and $\overset{o}{\eta_2}$ are calculated by taking the positive square root of $\overset{o\ 2}{\eta_1}$ and $\overset{o\ 2}{\eta_2}$ respectively.

14. $\overset{o}{\xi_1}$ and $\overset{o}{\xi_2}$ are calculated by taking the positive square root of $\overset{o\ 2}{\xi_1}$ and $\overset{o\ 2}{\xi_2}$ respectively.

15. $\overset{o}{A_1}$ and $\overset{o}{A_2}$ are calculated from equation (v) using $\overset{o}{\xi_1}$, $\overset{o}{\xi_2}$, $\overset{o}{V_A}$ and $\overset{o}{V_C}$.

16. $\overset{o}{A_1}$ and $\overset{o}{A_2}$ are calculated a second time from equation (v) using $\overset{o}{\eta_1}$, $\overset{o}{\eta_2}$, $\overset{o}{V_B}$ and $\overset{o}{V_D}$.

Various checks and comparisons are included during the calculations. These can be listed as follows;

1. A check is made to determine if there is no angle of arrival. This would mean that for the particular range annulus being examined that there was no radial velocity component corresponding to the Doppler

frequency being examined.

2. A check is made to determine if there is only one angle of arrival. In this case the output of the algorithm would give 0 for one of the two solutions.

3. A check is made to determine if there are three angles of arrival. The case of three angles of arrival can be detected but the three corresponding amplitudes and directions cannot be resolved using only four elements over 360^{o}.

4. A check is made to determine if there is shadowing of one antenna element by another. That is, one disconnected element may block or distort the electromagnetic signal before it reaches the element that is connected to the receiver at that scan period.

5. A quality figure is computed during the algorithm calculations for each received signal. This quality figure is computed as follows;

$$\text{QUALITY}\ (\alpha) = 10^{-x}\ (1 - \text{sine}^2\ \alpha\ -\ \text{cosine}^2\ \alpha)^2$$

where x = constant

Thus the highest quality would be 1 and the lowest would be 0. (If there were no noise then obviously from the trigonometric identity $\text{sine}^2\ \theta + \text{cosine}^2\ \theta = 1$, then QUALITY $(\theta) = 1.00$).
The quality figure is used as a weighting parameter for the addition of the radial vectors from each site.

6. The signal to noise ratio is computed for each angle of arrival. If this ratio is below a certain threshold then the measurement is rejected. This ratio is also used as a weighting parameter for the addition of the radial vectors.

The actual FORTRAN software listing of the algorithm looks quite different from figure 2. It is actually the same solution that has been rearranged and optimized for fast execution time in the LSI 11/23 computer. This software routine along with the rest of the data interpretation software is being tested by C-CORE for evaluation purposes. It is not available for publication in this report because of its proprietory nature. To date both forms of the algorithm have been closely examined with simulated data. C-CORE has obtained a copy of a raw data set collected by NOAA at the Straits of Juan de Fuca in 1979. This will be processed by existing data interpretation software as a precursor to further development.

It is important to note that while only two signals (nominal) are resolved by the algorithm for each Doppler frequency, there are thousands of Doppler frequencies or cells being examined for each time series. Each cell in the Doppler spectrum within the region of the 1st order Bragg lines is examined. Thus thousands of signals are resolved for the same time series. This explains how the complex waveforms from the receiving antenna array are separated. The final output for one time series corresponding to a single range gate is a plot of radial current against azimuthal angle.

If an exact diagonal spacing of $\lambda/2$ is used for the receiving array, a 180^{o} ambiguity in the calculated angle of arrival may develop for

the non-ideal case when noise is present. This effect has been verified at C-CORE using the algorithm and a hand calculator. If noiseless signals are used in the input with exactly $\lambda/2$ spacing then no error occurs. If the numbers are slightly perturbed then the 180^{o} flipping can be observed. No error in the recovered amplitude or phase angle results other than that related to the noise magnitude. Recent developments at NOAA seem to indicate that this angle flipping ambiguity can be resolved for exact $\lambda/2$ spacing. The present system uses a diagonal spacing of slightly less than $\lambda/2$ and no ambiguity results. This has also been demonstrated by simulation studies. In fact the spacing can be made infinitesimal and the algorithm still will give the same angle accuracy for simulated data. There are however practical reasons for keeping the spacing as close to $\lambda/2$ as possible. One of these reasons is the accuracy required in the system timing. Another would be antenna shadowing. The actual antenna spacing is entered into the algorithm as a parameter. It is not necessary that the spacing be geometrically symmetrical but the spacing must be measured exactly.

2.3 Hardware - A Functional Description

CODAR has over the last five years gone through a remarkably rapid, evolutionary development. There have been over three major hardware redesigns successfully completed to incorporate new theory and refined operational features. Under its "Transition Engineering Plan", NOAA is planning a major effort to update the documentation as well as providing a complete set of engineering specifications (CODAR Working Conference, 1980). Unfortunately this documentation will not be available until early 1982. This section contains a brief description of the present hardware which comprises the CODAR system. A system block diagram is shown in figure 3.

2.3.1 Computer Terminal

The operator at each radar station controls the entire operation from a CRT computer terminal. Communications with the computer is done through an interactive software package designed for CODAR that utilizes special attributes of a Digital Equipment Corporation Inc. (DEC) VT100 terminal. An "enhanced video option" board (VT1XX-AB) that plugs into the terminal is required by the software. Many other commercially available terminals could be used. However most would require costly changes to be made to the custom software employed in the system. A further advantage with the DEC terminal is that it can be bought under a system price with the rest of the DEC equipment required. This also makes any service contract for the computer and its peripherals simpler and thus more efficient to administer.

2.3.2 Computer

The choice of minicomputer was the DEC LSI 11/23 because all of the custom CODAR software has been written to run on that machine. Similar com-

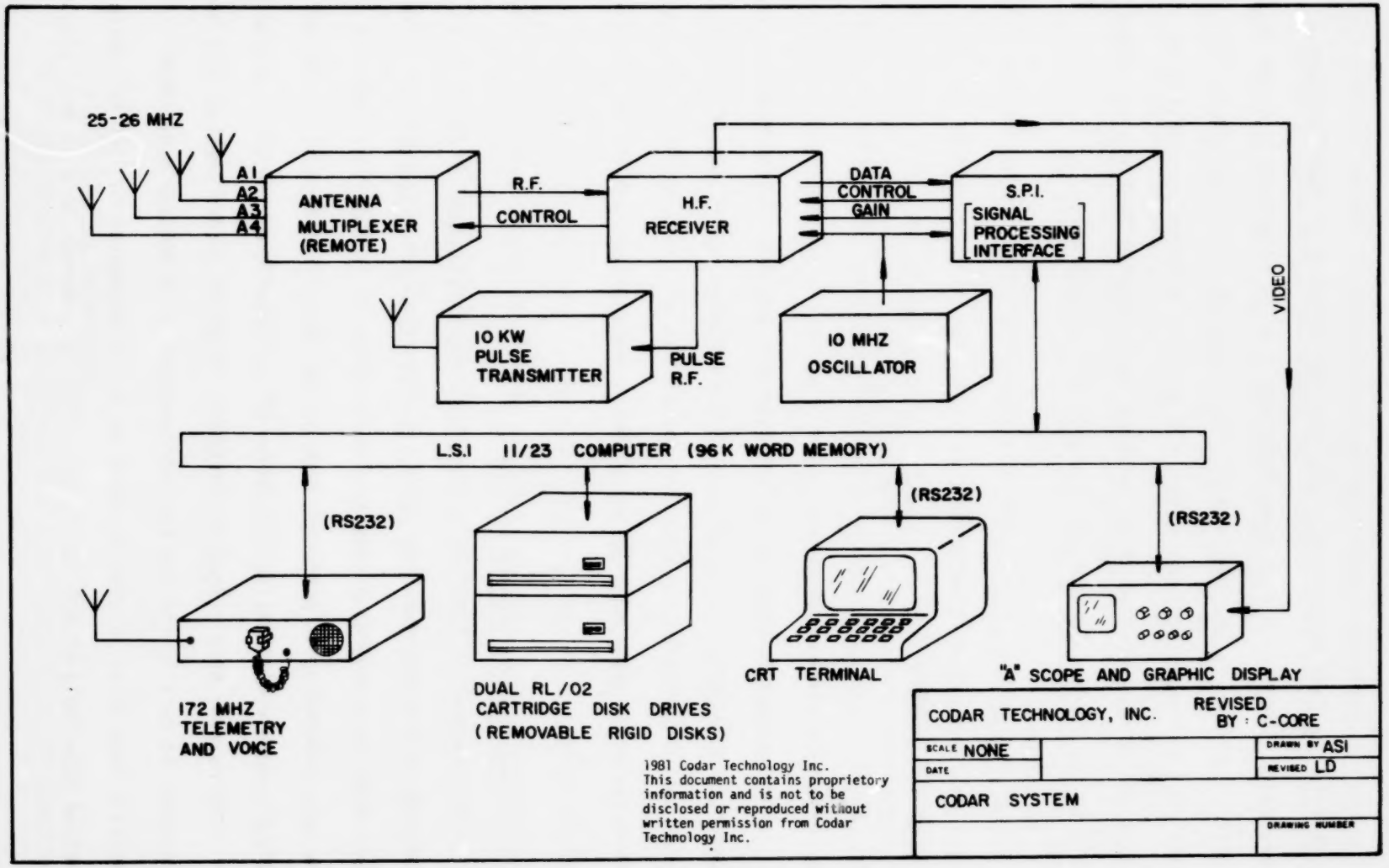

Figure 3: CODAR System Block Diagram

puters in the same family could also run the software if modifications were made. However at this time there would be no advantage in going to another computer in the same family line since the 11/23 represents the best cost to computing power ratio. It would be extremely expensive to adapt the 32 man-years worth of software to a computer that was not compatable to the 11/23. Some of its features and options are;

a) 16 bit word
b) 192 k bytes of memory
c) floating point arithmetic chip
d) memory management unit
e) bootstraps / diagnostic / PROM board
f) serial interface board
g) extensive software support

The interested reader is referred to the computer company manuals for a complete description. The function of the computer is central to the entire radar system operation. A detailed description of the computer's role in the CODAR system is supplied with the software description supplied in sections 2.4 and 2.5.

2.3.3 Computer Mass Storage Peripheral

The emphasis at NOAA has to date been the development of CODAR as a research tool rather than the application of CODAR in an operational sense. Thus while they have done some data interpretation in the field, most of the data processing is performed back in the lab. This mode of operation allows a more comprehensive evaluation of all aspects of the CODAR system.

The current NOAA system uses magnetic tapes to record the raw data and transport it back to the lab for interpretation. A Kennedy model 9700 magnetic tape drive is used to store up to 8.4 magabytes on 1600 BPI phase - encoded tape reels of 600 ft. length. This corresponds to a 35 min. single

station output. Newer, high density tape cartridges are presently being investigated by NOAA that will reduce the size and cost of both tapes and drives. One such system uses the 3M tape cartridge which will hold 8 times as much data in one-quarter the space required by a 600 ft. tape (Evans, personal communication, 1980). Meanwhile, C-CORE has proposed to develop CODAR as an operational tool and therefore will be using rigid disk drives in the field. The disk drives are necessary for efficient data processing because of their large data storage capability and fast random data addressing resulting in very high data transfer rates. No other currently available device can do this. However recent developments indicate that alternate bulk memory devices with enough data capability may soon become available that could replace a fixed rigid disk in field applications. (Electronics, 1981). It would not however provide a non-volatile memory, and when the power is turned off in returning from the radar site the data would be lost.

Two RL/02 disk drives containing 10 megabyte removable, rigid disk packs are presently available. However in light of the fact that fixed disk systems are subject to less environmental contamination, sealed Winchester disk drives are being recommended here. One disk would contain the CODAR software and the other could be used to store the 8.4 megabytes of raw data until the data interpretation phase of the operation commences. The resulting current vector map would then be stored back on the disk. Hundreds of such maps could be stored on one disk. This also leaves the option of bringing back a run of raw data if required. However, magnetic tape recording is still the preferred process for this purpose.

2.3.4 Signal Processing Interface

A specially designed printed circuit board called a Signal Processing Interface (SPI) is used to interface the computer to the radar system. It

was designed by NOAA to relieve the overhead on the computer's Central Processing Unit (CPU).

This board enables the computer to accommodate the extremely high data rate coming from the radar output. Its location in the system is shown in figure 3 and a block diagram of the board itself is shown on figure 4. It is composed entirely of digital logic circuits and is installed inside the LSI 11/23 computer chassis.

The SPI board has many features:

1. It provides a double storage buffer of 1024 bytes each for the data from the radar receiver.

2. There are eight user selectable data "windows" located in 2048 bytes of memory located on the SPI board used for the signal processing.

3. It performs a pre-averaging of the data from the radar transceiver using the above mentioned buffers and one of the sample enhancing windows. (A Blackman - Harris window has been used the most). One buffer is filled and used for the averaging while the other is available to dump previously averaged data to the computer main memory using a Direct Memory Access (DMA) process. One hundred and twenty-eight samples of 12 bits are weighted by the window constants and averaged to give one 16 bit sample. This provides a signal to noise improvement of the square root of 128 or 10.5 dB. The internal accuracy of these calculations is 32 bits. Thus the actual size of each buffer is 2048 bits. The least significant 16 bits of each buffer is ignored once the averaging is completed.

4. A direct memory access capability is built into the Q bus interface on the SPI board. This provides the maximum possible data rate transfer to the

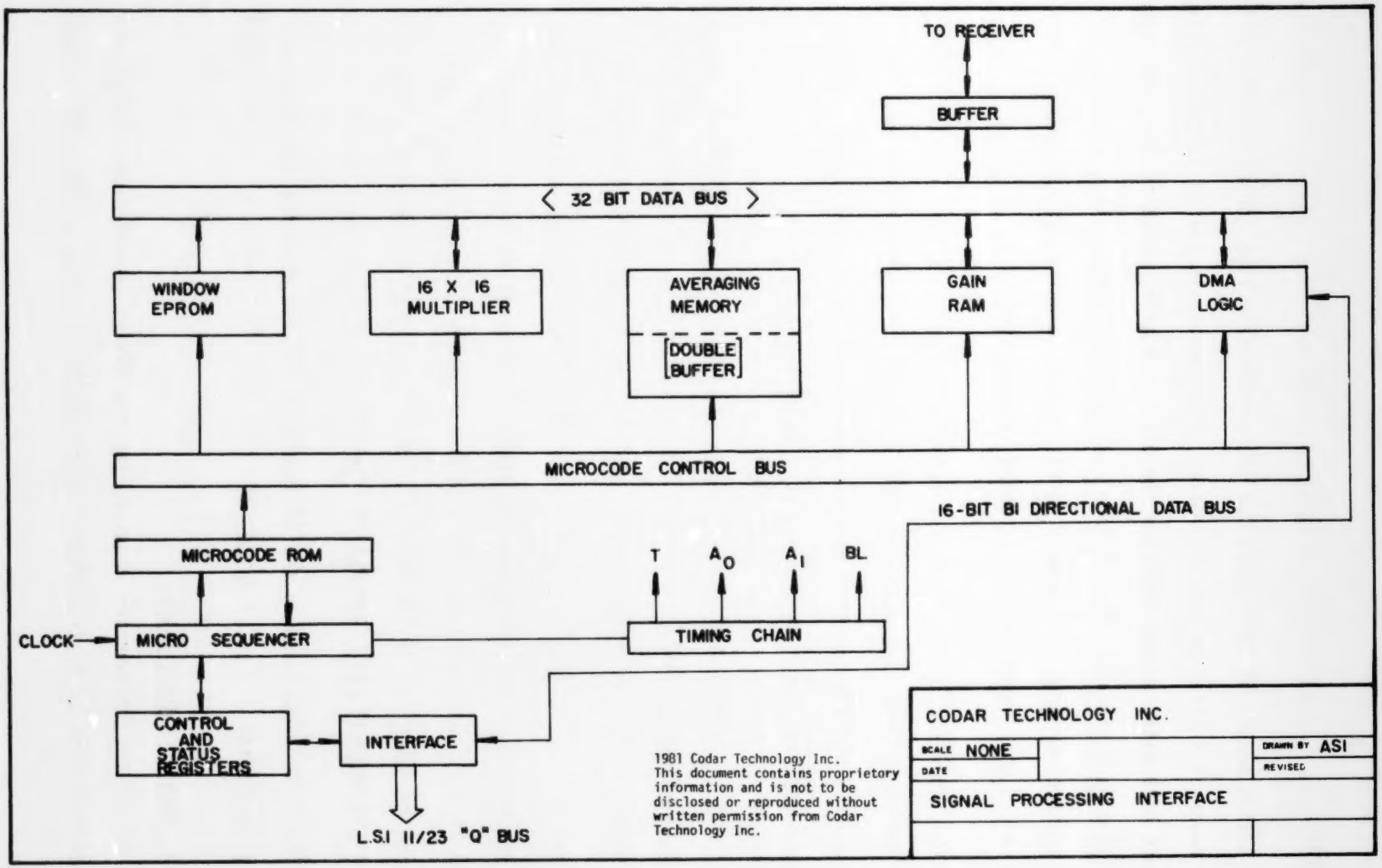

Figure 4: Signal Processing Interface Block Diagram

computer.

5. A gain memory of 1536 bytes for the Sensitivity Time Control (STC) of the radar is located on the SPI board. This memory is loaded by the computer before each data run and contains the digitized gain constants for each range cell for each antenna. One of four constants per range cell are passed to the transceiver from this memory corresponding to which antenna element is active and what range annulus is being interrogated.

6. The interface to the radar transceiver is over a 16 line digital bus. Four of these lines are control lines and 12 are a bidirectional data bus. Twelve bits of gain control constants are passed back from the SPI to the transceiver over these same lines at a later time.

7. There is extensive self diagnostics implemented in the design of the SPI which can detect a fault in the logic circuits before any erronous data can be logged, a feature which proves invaluable to a real time operation.

8. The SPI also allows a powerful test of the interface to the transceiver and the Analog to Digital Converter (ADC) and Digital to Analog Converter (DAC) in the radar receiver. On a signal from the SPI the output of the DAC can be connected to the input of the ADC. Simulated radar data can then be passed through this connection from the SPI board.

9. The 2 MHz clock used on the SPI board is derived from the system master 10MHz oscillator discussed below.

2.3.5 Reference Oscillator

All of the frequencies required for the mixers in the radar transceiver are derived from an Austron 1120L 10MHz oscillator using a frequency synthe-

sizer as shown in figure 5. The quartz crystal oscillator is oven stabalized and contained in a hermetically sealed module mounted in the transceiver chassis.

2.3.6 Transceiver Package

The HF transceiver package contains the radar transmitter and receiver. It is shown in figure 5. It also contains the ADC for converting the anlog information of the radar into a digital number as discussed above. It contains two IF strips that translates the information modulated on the radar carrier to a baseband or 0 Hz frequency offset. The transmit frequency is between 25 and 26 MHz selected in 50 KHz steps by the operator.

The present transceiver is being built by a company called Erbtec Engineering and sold by CTI. It is a custom receiver design and is implemented in a series of plug-in printed circuit boards for modularity of design and ease of maintenance. It evolved from a design by Barry Research Corporation and is not available from any other commercial source. It would not be practical to try and duplicate this design in-house. A detailed specification is not presently available.

2.3.7 Transmitter Driver Amplifer

The output of the radar transmitter is a short pulse CW signal of 10dBm amplitude. This output must be boosted up in power to several hundred watts before it can be fed into the final power amplifier. There are a vast number of commercially available units that can adequately perform this task and they can be specified at a later date.

2.3.8 Transmitter Power Amplifier

The final amplification stage accepts the output of the driver amplifier

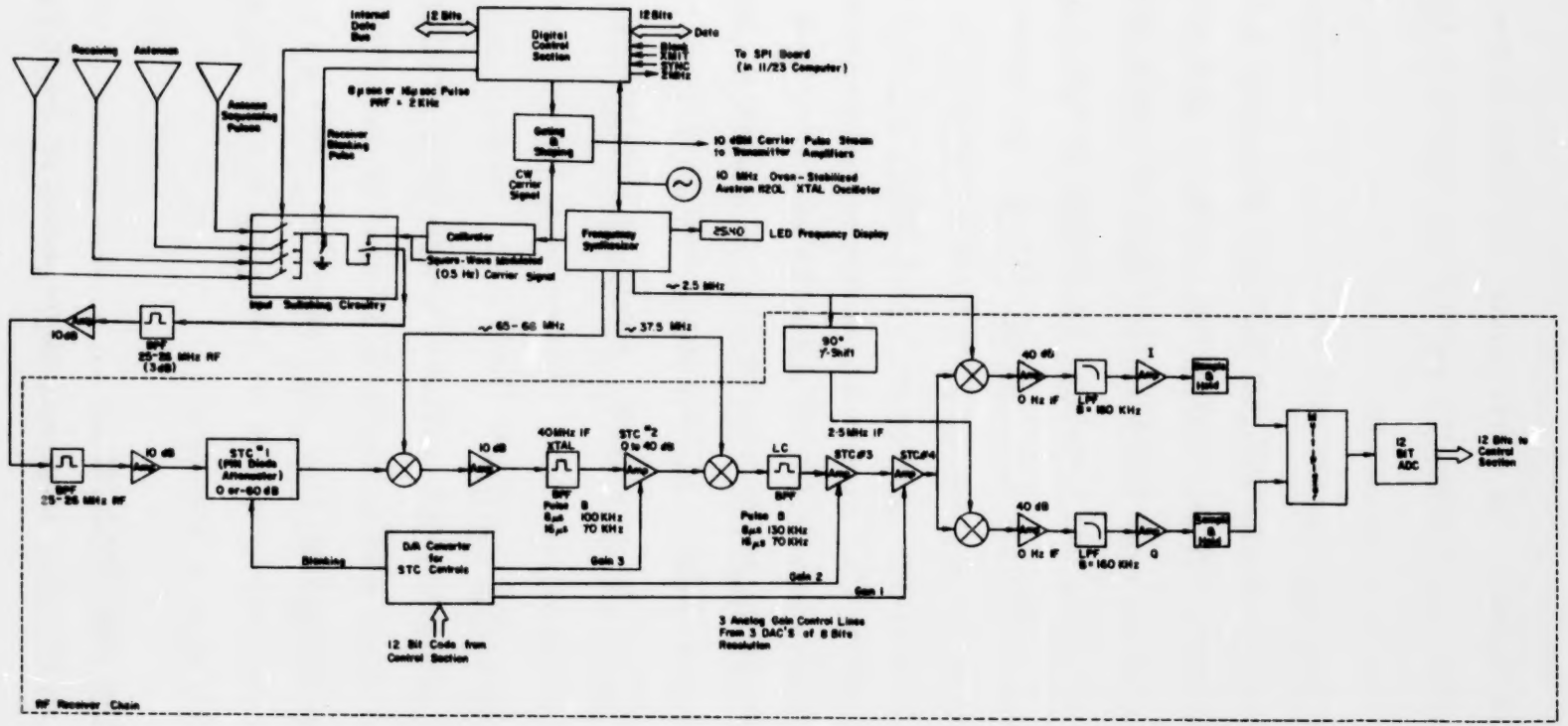

Figure 5: Transceiver Block Diagram

discussed above and boosts it further to about 10 kilowatts peak for final transmission. The present NOAA system uses a modified amateur unit, however as with the driver, there are several commercially available units that can be used.

2.3.9 Transmitter Antenna

The transmitter antenna can be either a single omnidirectional whip antenna or a $\pm$ 90° beamwidth Yagi antenna as discussed earlier in this report. Both should be coupled efficiently to a good ground plane to reduce antenna losses.

Basically the omnidirectional antenna is a ¼ λ high whip antenna with ground plane. It is designed for rapid deployment and is easily transported.

The general Yagi antenna has been used for many years and its performance is well established. A design and computer study was performed at Lawrence Livermore Laboratories to optimize its performance for the CODAR system while maintaining a physical size and shape to allow rapid deployment, some frequency selection and small size. The result has been an adjustable antenna with some of the following features for 25 MHz.

a. 3 X 2.54 cm diameter vertical elements
b. reflector height = 3.19 m
c. driver height = 3.19 m
d. director height = 2.57 m
e. reflector - driver spacing = 2.70 m
f. driver - director spacing = 0.627 m
g. 3 dB beamwidth = 180°

The length, diameter and spacing of the vertical elements are critical and would require modification with small changes in frequencies. The spacing can be adjusted using a sliding bar design. The elements may or may not need replacing depending on the magnitude of frequency change specified.

The blueprints for both the transmitter antennas and the reciever antenna arrays have been supplied by NOAA. The antennas can be readily constructed locally. These antennas are discussed in more detail by Barrick and Evans (1976).

2.3.10 Receiver Array Multiplexer and Pre-Amplifier

At the center of the receiver array is a small box containing the antenna multiplex, a pre-amplifier, a Transmit - Receive (TR) switch and a bandpass filter The purpose of the multiplexer is to sequentially connect each of the four receiver antenna elements to the receiver while disconnecting the remaining three elements in accordance with the operation of the array as already discussed in section 2.1. It is a time division multiplexer and its operation is controlled by the antenna sequencing pulses supplied by the transceiver.

The bandpass filter provides a nominal amount of noise rejection before the signal reaches the receiver.

A pre-amplifier makes up for the losses in the filter and coaxial cable. It also boosts the signal above the basic noise background to retain signal fidelity over the long antenna feed cable.

The TR switch disconnects the receiver array from the receiver during transmission of the radar pulse. This protects the sensitive components in the front-end of the receiver. The TR switch is controlled by the receiver blanking pulse.

All of the pre-receiver components are inexpensive and can be fabricated in-house.

2.3.11 Receiver Array

The operation of the receiver array was discussed in sections 2.1 and 2.2 of this report.

2.3.12 Graphics Module

The graphics module is a microcomputer (Intel 8085) based display system that is hooked to the LSI 11/23 computer through a serial digital interface. The "video" or baseband analog information from the HF receiver is routed directly to the module as shown in figure 3. The module display provides a check on equipment operation and data quality thus making it essential for real-time diagnostics. Operation of the rest of the CODAR system does not require this module.

The following information can be displayed automatically or manually selected;

a. Receives I or Q video outputs for antennas one through four.
b. Composite video (square root of sum of squares for I and Q).
c. 32 second FFT power spectrum
d. I or Q digital time series
e. User - generated graphic plots.

The subsystem contains a microcomputer board that accepts plotting commands from the computer and using the DAC's plots the information on a bistatic storage CRT or routes the video signals directly to the CRT depending on the mode selected.

The most cost effective implementation would be to use a standard storage tube to replace the modified HP CRT display monitor used by NOAA.

This unit may be redesigned at C-CORE if time permits, meanwhile NOAA's design is available.

2.3.13 Incremental Plotter

When data interpretation is complete it is necessary to provide a hard copy output of the mapped vector current field. This is presently done by NOAA using a Nicolett Zeta Corp. model 1553 high speed digital XY plotter.

This appears to be the logical choice for present application to CODAR since most of the software has now been developed. This plotter is also the same one used in-house by C-CORE's computer group.

2.3.14 VHF Telemetry Link

A telemetry link is required between the two stations of the CODAR system for efficient coordination of the data acquisition phase and real-time operation. Both a data and voice link are required. A telephone link would be sufficient if available.

The present NOAA system uses a VHF radio link where a phone line is not available (this will occur in the vast majority of sites selected). They have modified a 60 - watt Motorola Micor mobile radio to transmit and receive both voice and data at 1200 baud, using conventional FSK.

However, since the above telemetry system was designed several mobile radios have become available that are better suited for this application. The new radios incorporate a digital modulation system for voice communications. Thus they are optimized for sending digital information. They can provide an order of magnitude faster baud rate using the same bandwidth as the NOAA telemetry system. Since the basic information format is digital, interfacing or adapting the radios for CODAR operation will be straight forward. They would also provide a longer range for the same operating power. Discussions are currently underway between CTI and C-CORE to define a development strategy for CODAR data communications.

2.4 Software - Data Acquisition

CODAR computer software can be classified under three major headings:

1. Data acquisition
2. Data interpretation
3. Simulation and logistics

The data interpretation software is discussed in section 2.5 and the simulation and logistics software which is used for test and development work will not be discussed. A block diagram of the complete data acquisition phase of CODAR operation is shown in figure 6.

The operator controls the entire operation through an interactive software monitor. This control package is part of the data acquisition software and runs under the DEC operating system RSX-11S. A more flexible DEC operating system RSX-11M is used for development and re-processing at the laboratory.

The first phase of a data acquisition operation consists of system initialization. The operator must respond to a series of computer prompted questions. Some of these parameters are as follows:

1. Latitude and longitude of each station
2. Time and date
3. Receiving antenna baseline orientation
4. Radar operating frequency selected
5. Radar pulse width selected
6. Length of time series selected
7. Relevant meteorological data (such as wind, speed, direction, tidal phase) for later referral and correlation.

The computer then initializes all hardware and performs a hardware check. A sample radar run is completed to insure correct system operation and assesses any noise or interference present. When this stage is complete, the computer reports to the operator who then initiates the radar run.

The next stage is the actual data collection. First the analog data from each receiver antenna is multiplexed and amplified up to a level to be passed to the receiver. The receiver then provides the necessary amplification,

CODAR DATA ACQUISITION FOR CURRENT-VECTOR MAPPING

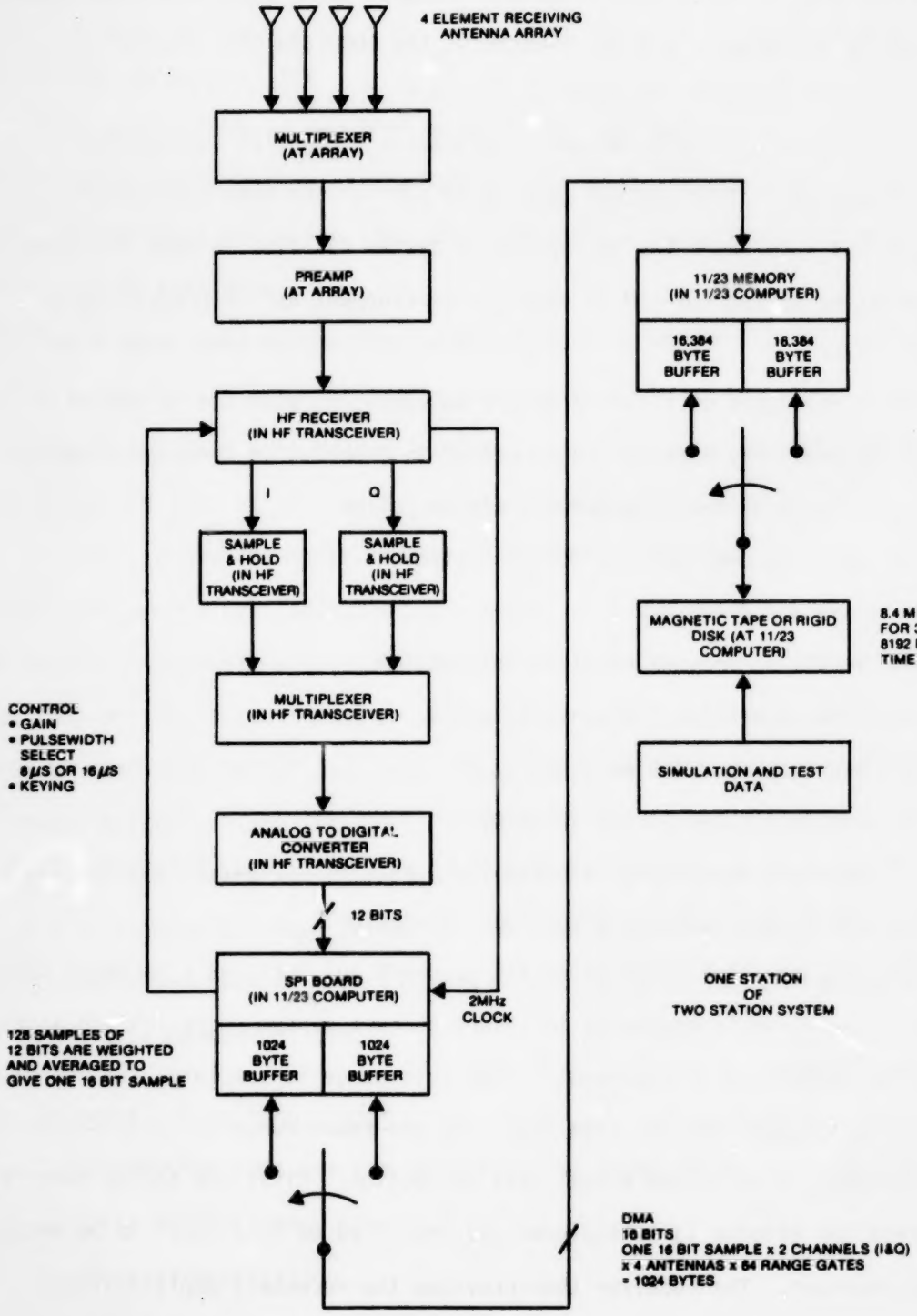
4 ELEMENT RECEIVING ANTENNA ARRAY
MULTIPLEXER (AT ARRAY)
PREAMP (AT ARRAY)
HF RECEIVER (IN HF TRANSCEIVER)
I
Q
SAMPLE & HOLD (IN HF TRANSCEIVER)
SAMPLE & HOLD (IN HF TRANSCEIVER)
MULTIPLEXER (IN HF TRANSCEIVER)
ANALOG TO DIGITAL CONVERTER (IN HF TRANSCEIVER)
12 BITS
SPI BOARD (IN 11/23 COMPUTER)
1024 BYTE BUFFER
1024 BYTE BUFFER
2MHz CLOCK
CONTROL
• GAIN
• PULSEWIDTH SELECT 8μS OR 16μS
• KEYING
128 SAMPLES OF 12 BITS ARE WEIGHTED AND AVERAGED TO GIVE ONE 16 BIT SAMPLE
11/23 MEMORY (IN 11/23 COMPUTER)
16,384 BYTE BUFFER
16,384 BYTE BUFFER
MAGNETIC TAPE OR RIGID DISK (AT 11/23 COMPUTER)
8.4 M BYTES FOR 35 MIN. RUN 8192 POINT COMPLEX TIME SERIES
SIMULATION AND TEST DATA
ONE STATION OF TWO STATION SYSTEM
DMA
16 BITS
ONE 16 BIT SAMPLE x 2 CHANNELS (I&Q)
x 4 ANTENNAS x 64 RANGE GATES
= 1024 BYTES

Figure 6

filtering and coherent demodulation. All controls are received from the computer via the SPI board. The output of the receiver is two channels labelled In-phase and Quadrature (I & Q). These two channels are required as the complex input to a complex Fast Fourier Transform as discussed later.

Next the I & Q channels are fed to separate sample and hold circuits before being fed to a 12 bit ADC through a multiplier circuit. The data is now in digital form ready to be passed to the computer via the SPI board. This process loops until the selected run time is complete. There are 805 megabytes of information collected at each station for a 35 min run, corresponding to an 8192 point complex time series. The signal processing at the SPI reduces this to 8.4 megabytes which has been called the "raw data" in this and other reports. A detailed description of this processing in the SPI is given in section 2.3.

Next the data is buffered to the LSI 11/23 computer for fast data transfer. The computer directs 16 DMA cycles to fill half of a double buffer in main memory. Once this buffer is filled then another DMA action transfers this block of data to the mass storage device.

The computer uses the above mentioned buffer to provide a running diagnostic to the operator. Intermediate short FFT's are performed and displayed on the graphics subsystem. A check of signal to noise ratio is also updated for the returned signal.

During the dump of the data to mass storage device a read after write check is performed. In the case of some magnetic tape drives there is not enough time for the system to correct these errors. Instead a special file is appended to the tape after the data run is complete to keep track of these errors. Meanwhile, the operator is continually updated as to their number to allow for detection of contaminated tapes and/or equipment malfunction.

2.5 Software - Data Interpretation

Data interpretation for CODAR current vector mapping is performed entirely as a software function that can be run on any LSI 11/23 software compatible computer. C-CORE has obtained a complete copy of this software for evaluation purposes. However, the listing cannot be included in this report because of its proprietory nature. A raw data set has also been supplied by NOAA to "exercise" this software.

A flowchart for data interpretation is shown in figure 7. Range gating or sorting of the I & Q channels must first be performed. A complex time series for each of the four antennas for each of the 64 range rings is then set up.

Next four independent frequency (Doppler) spectra are produced from the four time series using a complex Fast Fourier Transform (FFT) algorithm.

Following the FFT, each of the four Doppler spectra are windowed to remove all but the first-order sea returns. The second-order region also contains information about the ocean spectrum but is not needed for mapping current vectors. The width of these windows and hence the number of data points retained for processing is directly proportional to the largest radial current component encountered on the circular range annulus. The window is formatted automatically by the software depending on the shape of the first order signal spectra. Thus an adaption to noise and site conditions is made. The number of times the next loop in the diagram is performed will depend on this adaptation.

Now for each designated doppler frequency, the four complex voltages representing each antenna are selected and the azimuth angle finding algorithm is applied. This block has been described in detail in section 2.2.

Next the signal to noise ratio associated with each return is used to reject any noise distorted measurements. The rejection threshold constant is preset by the operator. Any decrease in the signal to noise level below this level will

CODAR DATA INTERPRETATION FOR CURRENT-VECTOR MAPPING

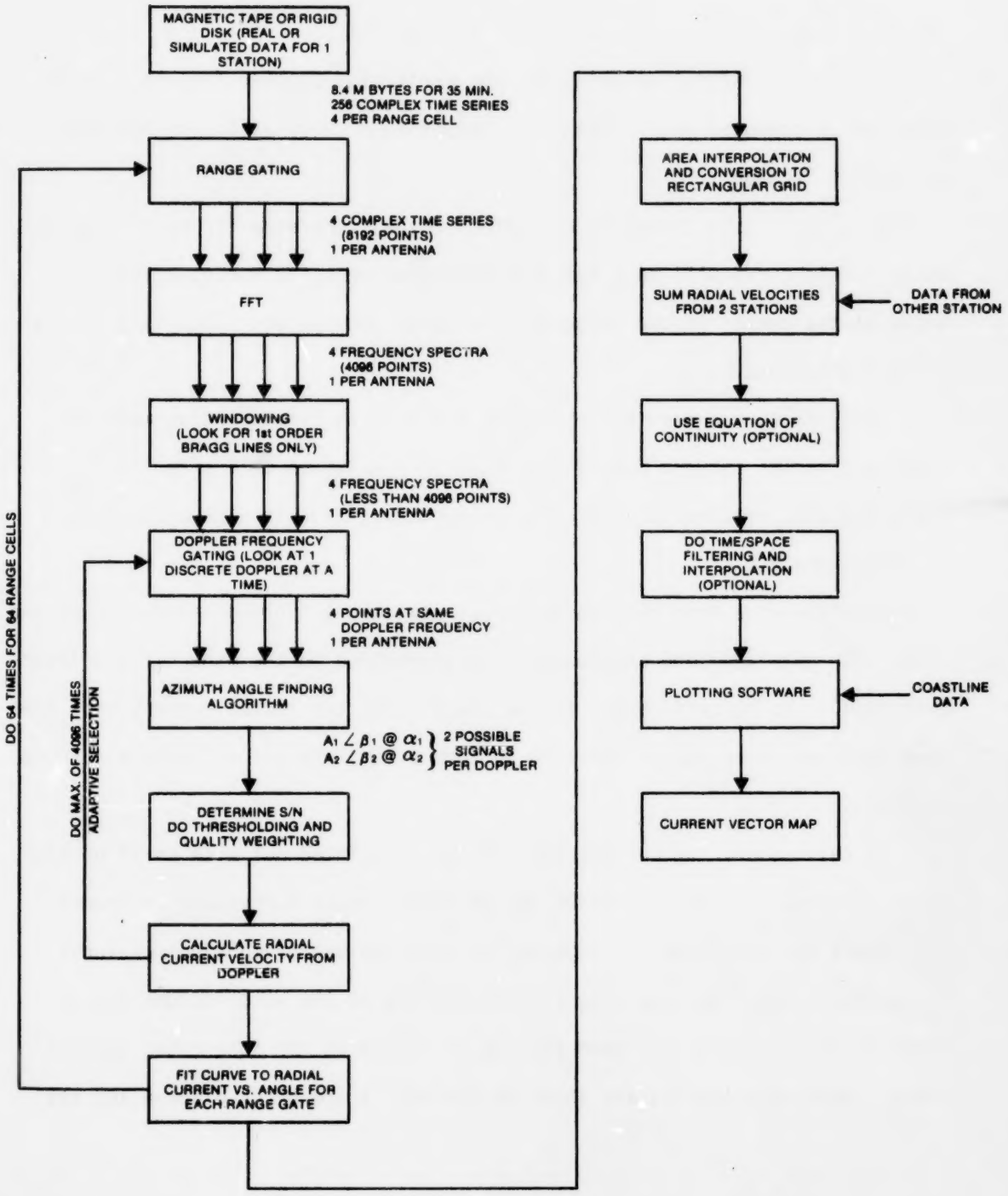
MAGNETIC TAPE OR RIGID DISK (REAL OR SIMULATED DATA FOR 1 STATION)
8.4 M BYTES FOR 35 MIN.
256 COMPLEX TIME SERIES
4 PER RANGE CELL
RANGE GATING
4 COMPLEX TIME SERIES (8192 POINTS) 1 PER ANTENNA
FFT
4 FREQUENCY SPECTRA (4096 POINTS) 1 PER ANTENNA
WINDOWING (LOOK FOR 1st ORDER BRAGG LINES ONLY)
4 FREQUENCY SPECTRA (LESS THAN 4096 POINTS) 1 PER ANTENNA
DOPPLER FREQUENCY GATING (LOOK AT 1 DISCRETE DOPPLER AT A TIME)
4 POINTS AT SAME DOPPLER FREQUENCY 1 PER ANTENNA
AZIMUTH ANGLE FINDING ALGORITHM
A1 ∠ β1 @ α1
A2 ∠ β2 @ α2
2 POSSIBLE SIGNALS PER DOPPLER
DETERMINE S/N DO THRESHOLDING AND QUALITY WEIGHTING
CALCULATE RADIAL CURRENT VELOCITY FROM DOPPLER
FIT CURVE TO RADIAL CURRENT VS. ANGLE FOR EACH RANGE GATE
DO 64 TIMES FOR 64 RANGE CELLS
DO MAX. OF 4096 TIMES ADAPTIVE SELECTION
AREA INTERPOLATION AND CONVERSION TO RECTANGULAR GRID
SUM RADIAL VELOCITIES FROM 2 STATIONS
DATA FROM OTHER STATION
USE EQUATION OF CONTINUITY (OPTIONAL)
DO TIME/SPACE FILTERING AND INTERPOLATION (OPTIONAL)
PLOTTING SOFTWARE
COASTLINE DATA
CURRENT VECTOR MAP

Figure 7

just be reflected in rejection of those vectors on the current map. This accounts for the irregular shape of some vector maps presented in the literature. Severe reduction in range due to reduced signal to noise has been infrequent and has not persisted (Appendix A).

The radial current velocity for the particular Doppler frequency being examined is computed next. This is a very simple calculation and has been derived in Section 1.1.

A curve is then fitted to the set of points generated for each range annulus. This curve will be a function of radial velocity versus azimuthal angle at the center of the range annulus being considered. This is a spatial filtering process.

After 64 curves have been computed there is an interpolation made to compute a radial current map of the required resolution cell size. This involves the conversion to a rectangular grid of vectors. This is also a spatial filtering process.

Next the maps from the two identical stations are brought together at one site. The data from one station will be telemetred to the other if the interpretation is to be carried out in the field. The two radial current maps are then combined using vector addition to form a complete set of surface current vectors.

At this point, the current vectors may be printed out with an XY plotter which can also include an outline of the site's coast for visual reference.

There has been some experimentation with the use of multi-dimensional filtering to describe upwelling and downwelling in the water column and an equation of continuity has been applied to interpret for "one site" applications. Both calculations are shown as options in the block diagram and are

not considered in the discussion of this report. Dr. D. Barrick discusses these applications further in the "Verbatim Transcript of C-CORE HF Radar Seminar at Memorial University (Appendix A).

3.0 TECHNOLOGY TRANSFER PROGRAM

The potential of HF radar for the remote measurement of coastal and offshore sea state and surface currents has been clearly demonstrated by CODAR. It is also our belief that CODAR is only the stepping stone to a technology that may hold the key to reliable ice hazard detection and tracking for offshore exploration and Arctic transportation. However, before we proceed on the related avenues for applications, it is important that we fully understand the limitation of this technology. A technology transfer program to bring the state-of-the-art on the subject to the community is thus a logical first step to further development.

A block diagram description of the technology transfer activity plan is presented in Figure 8. The bulk of the feasibility function indicated with the dotted line has already been completed and is partially reported here. A work schedule is also presented in figure 9.

Please take note of the activity in figure 9 labled "Establish Analytical Program To Guide Ice Radar Development". This item has replaced an originally proposed iceberg monitoring field program. In view of the large expense that would have been incurred for just one empirical study over a single ice type the program has instead been changed to include a broader analytical approach to the entire problem of ice hazard detection involving all ice types. The program will primarily involve the group of researchers already engaged in radio propagation and scattering studies at Memorial University of Newfoundland and will exist in parallel with the transfer program at C-CORE. Plans for effective use of CODAR technology in empirically assisting this study are nearing completion. Cooperation between C-CORE researchers and Memorial faculty is continuing to grow and is expected to form a healthy research atmosphere unique to Canada.

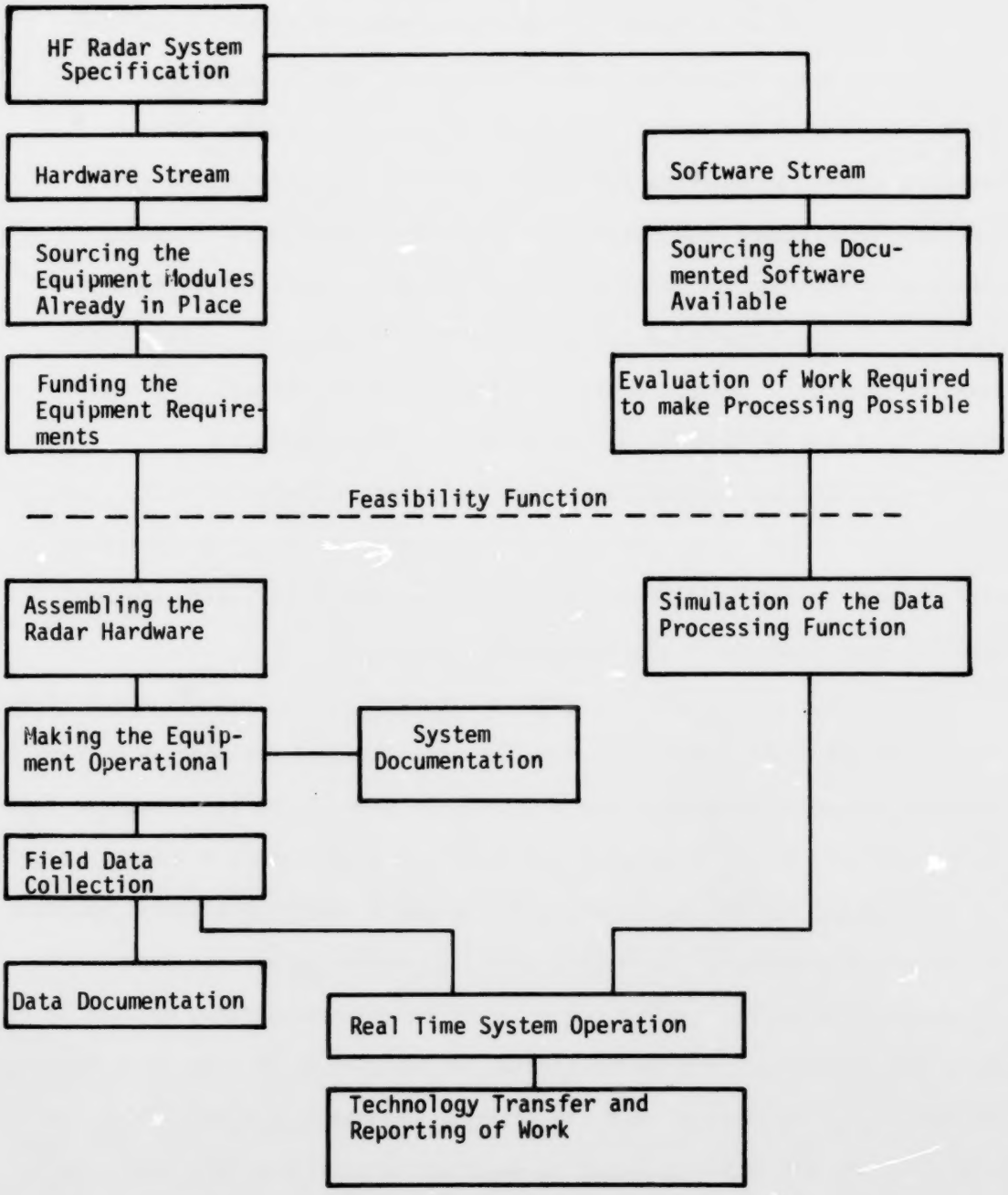
HF Radar System Specification
Hardware Stream
Software Stream
Sourcing the Equipment Modules Already in Place
Sourcing the Documented Software Available
Funding the Equipment Requirements
Evaluation of Work Required to make Processing Possible
Feasibility Function
Assembling the Radar Hardware
Simulation of the Data Processing Function
Making the Equipment Operational
System Documentation
Field Data Collection
Data Documentation
Real Time System Operation
Technology Transfer and Reporting of Work

Figure 8: Activity Block Diagram

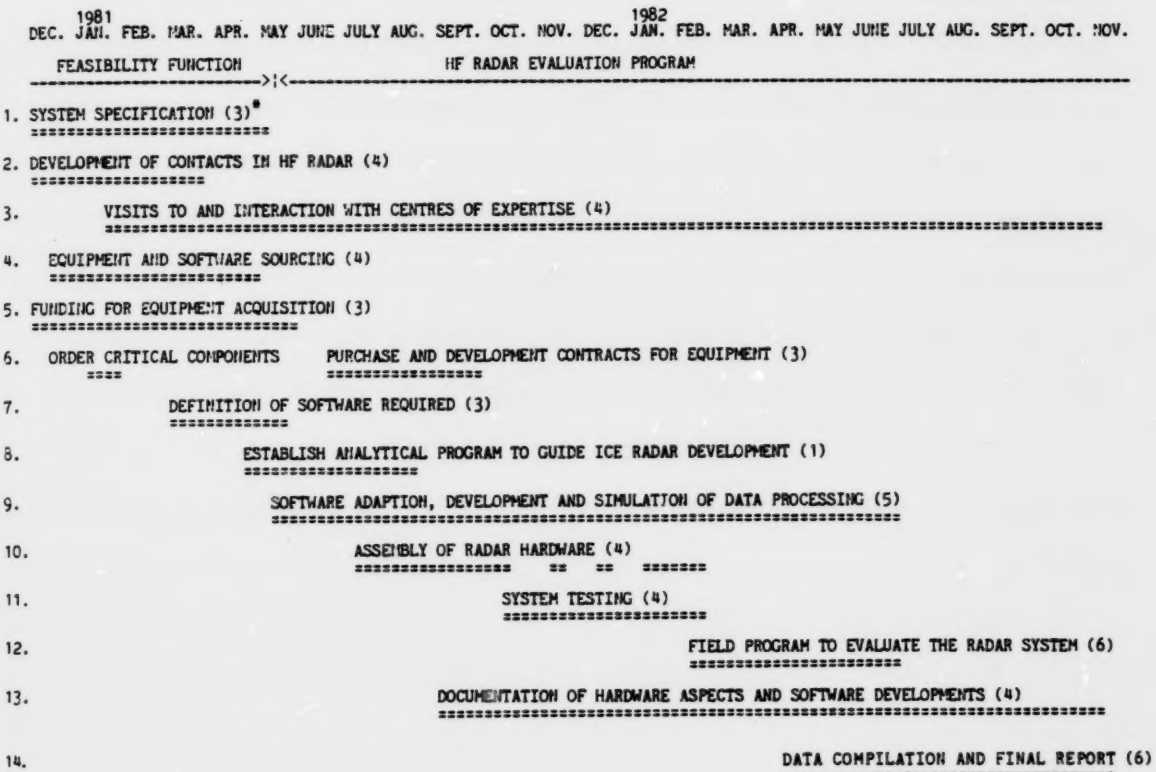
1981
DEC. JAN. FEB. MAR. APR. MAY JUNE JULY AUG. SEPT. OCT. NOV.
1982
DEC. JAN. FEB. MAR. APR. MAY JUNE JULY AUG. SEPT. OCT. NOV.
FEASIBILITY FUNCTION
HF RADAR EVALUATION PROGRAM
1. SYSTEM SPECIFICATION (3)*
2. DEVELOPMENT OF CONTACTS IN HF RADAR (4)
3. VISITS TO AND INTERACTION WITH CENTRES OF EXPERTISE (4)
4. EQUIPMENT AND SOFTWARE SOURCING (4)
5. FUNDING FOR EQUIPMENT ACQUISITION (3)
6. ORDER CRITICAL COMPONENTS
PURCHASE AND DEVELOPMENT CONTRACTS FOR EQUIPMENT (3)
7. DEFINITION OF SOFTWARE REQUIRED (3)
8. ESTABLISH ANALYTICAL PROGRAM TO GUIDE ICE RADAR DEVELOPMENT (1)
9. SOFTWARE ADAPTION, DEVELOPMENT AND SIMULATION OF DATA PROCESSING (5)
10. ASSEMBLY OF RADAR HARDWARE (4)
11. SYSTEM TESTING (4)
12. FIELD PROGRAM TO EVALUATE THE RADAR SYSTEM (6)
13. DOCUMENTATION OF HARDWARE ASPECTS AND SOFTWARE DEVELOPMENTS (4)
14. DATA COMPILATION AND FINAL REPORT (6)
NOTE ··· * REPRESENTS THE NUMBER OF PEOPLE INVOLVED IN EACH PHASE.

Figure 9

A key question in any technology transfer project is the accessibility of the technology. The NOAA Group has spent over 32 man-years developing the present state-of-the-art computer software for surface current mapping and considerable effort on hardware engineering. The development costs of CODAR were high. NOAA has provided significant portions of their software to C-CORE for evaluation at no cost with the understanding that in the event that industrial support is established, then the appropriate terms of remunevation will be discussed. To further assist in the technology transfer, a company headed by the original CODAR program manager, Mr. M.W. Evans, has grown from the work of the NOAA Group. Called CODAR Technology Inc. (CTI), the company's mandate is to provide consultation and design services for HF radar applications. Appendix C describes this corporate entity in more detail. C-CORE has already entered into some minor contract arrangements with CTI although most of the information retrieval has been at no cost. It is anticipated by both parties involved (ie: C-CORE and CTI) that any Canadian development torwards ice hazard detection will result in a benefit to the U.S. as well.

Recently a seminar was held by C-CORE and the Ocean Engineering group at Memorial University of Newfoundland on the topic of HF surface and skywave radar systems. The speakers were Dr. D.E. Barrick and Dr. T.M. Georges of NOAA and Mr. M.W. Evans of CTI. Representatives of the Newfoundland Government, Canadian Coast Guard, Atlantic oceanographic research community, local academic community and local industry were present for the two hour presentation. A complete verbatium transcript of the seminar is included in Appendix A and keywords are underlined throughout. Most questions regularly asked by all those interested in CODAR applications were answered after the presentation by D.E. Barrick and M.W. Evans.

Although this report deals primarily with the concepts of surface wave propagating HF radar, it is important to note there is an active skywave Over-The-Horizon (OTH) radar research program in Canada (Butt, et.al., 1981). The technique attributes its name to the fact that the radio waves are transmitted beyond the horizon by "bouncing" the signal off an ionized layer of the Earth's atmosphere called the ionosphere. Subsequent to reflection from the ocean surface, the signal is returned to the receiver via the same ionospheric path. The backscattered signal has been shaped by the ocean's surface and through careful mathematical interpretation the information on the ocean's signature can be extracted.

In June 1980, C-CORE and the Communications Research Centre (CRC) in Ottawa began a joint program to establish the feasibility of applying the latest developments of this technology to the Canadian east coast sea and ice conditions. Supported primarily with Department of Fisheries and Oceans (DFO) funding, C-CORE has undertaken the responsibility of interpreting the first results using the classical techniques developed by other groups in the U.K. and the U.S.A.

Some of these techniques are briefly described by Dr. T.M. Georges of NOAA in the "Verbatim Transcript of C-CORE HF Radar Seminar at Memorial University of Newfoundland" (Appendix A).

4.0 FUTURE DEVELOPMENT

Central to the Canadian interest, though many basic questions still remain unanswered, is the potential of this type of radar system to detect ice conditions or iceberg targets. This conjecture is based on the fact that the signal return from an iceberg or ice cover at the sample cell cannot have undergone the Bragg scattering which results from the diffraction grating caused by wave patterns of an open sea. In fact, an ice covered ocean might be expected to act as a smooth plane target to the transmitted beam and detection could result from the absence of the wave induced Doppler shift. Conversely, the radar cross section of an iceberg can be described basically as a hole in the ocean where the edge of the hole could be expected to act as a corner reflector thus increasing the strength of return for that cell only.

Further examination of the "hole" concept gives rise to the suggestion of an application to an entire ice field. The electrical properties of first year sea ice and that of older consolidated ice floes and ridges differ considerably. It is expected that at HF, surface propagation over first year sea ice (ie: high conductivity) would be relatively uniform. However, if sharp impedance discontinuities such as a severe drop in average conductivity over an effective wavelength were encountered it is conceivable that energy will be reflected at the boundary mismatch. Although resolution at HF would not be high as compared to conventional microwave imaging radars, it may be sufficient to image those obstacles deemed hazardous to shipping.

In March 1980, C-CORE and Ocean Engineering at Memorial University established a comprehensive empirical and analytical program to evaluate

this hypothesis. Graduate studies have been initiated under the supervision of Dr. John Walsh and a recent application to the National Science and Engineering Research Council (NSERC) of Canada has been filed under the strategic category of importance for assistance to carry out the field work described.

The potential of using HF Radar as a tool to study iceberg behaviour is very exciting. The threat of an iceberg collision with offshore platforms is a major concern for offshore development on Canada's East Coast. The questions of forces on impact, maximum iceberg size to expect and what countermeasures activity are open to much debate; a debate which will not be effectively resolved until there is more detailed knowledge on sighting statistics and of the natural forces that cause iceberg motion. The HF Radar alone, or, in the initial phase when system truthing is necessary HF Radar in conjunction with a PPI marine radar, could track both the iceberg movement and the surface current of the water mass transporting the iceberg. This ability to track the surface current in a spatial or Lagrangian sense is in contrast to past work where the only current description to support iceberg dynamics were single point moorings normally spatially separated from the iceberg. Data available on iceberg tracks suggest ocean current vectors vary radically over short horizontal distances and a current at one point may not describe the current field a kilometre away due to lack of coherence within the field. This in turn can ultimately provide the knowledge to plan more effective countermeasures schemes and provide a measurement tool to support iceberg drift forecast models.

5.0 CONCLUSIONS

The content of this report represents the results of C-CORE research in evaluating the effort needed to establish an HF surface wave radar technology for application to the Canadian marine environment. Attention was focussed on a specific system called CODAR (Coastal Ocean Dynamics Application Radar). Developed by the National Oceanic and Atmospheric Administration (NOAA), CODAR relies upon a resonant backscatter principle common to similar sea state mapping radars under development in other countries. However, innovative application of a phase measuring technique with high speed computer technology has produced the state-of-the-art for remote surface current mapping in a portable sense.

It is believed that CODAR can provide a sound basis for growth of HF electromagnetic analysis as applied to many aspects of oceans management. Although only the "current" mapping function was outlined, CODAR's modular design and computer systems approach can facilitate cost effective expansion to other applications such as directional ocean wave spectra measurements from an offshore platform, and transponder tracking for long range velocity and position measurements. A discussion of possible applications to ice research was included with a brief outline of C-CORE's intended activity.

The funding for such a large program is seen to grow from cooperative contributions from many sources. It is reasonable to forecast that support for the research and development will come from both industry and government as the benefits arising from this technology can directly influence many aspects of offshore activity.

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APPENDIX A

Verbatim Transcript of C-CORE HF Radar Seminar at Memorial University of Newfoundland (MUN)

Chairman: Dr. Ross Peters, Associate Dean of Engineering, MUN

Speakers: Dr. Donald E. Barrick
Chief, Sea State Studies Program Area
National Oceanic and Atmospheric Administration (NOAA)

Mr. Michael W. Evans
President, CODAR Technology, Inc.

Dr. Tom Georges
Skywave Sea State Radar Project
NOAA

Date: January 29, 1981 at 2:00 pm to 4:30 pm.

Place: S.J. Carew (Engineering/Geology) Building
Memorial University of Newfoundland
St. John's, Newfoundland

Room X-403

HF Radar Seminar

Dr. Peters

We are pleased to present this seminar. This project is very active at the moment and has been growing over the last year or so in C-CORE and also involves Dr. John Walsh from our Faculty. The gentlemen we are going to introduce are from the United States and are involved in the project. It is nice now and then to be able to make a point of the fact that there are joint projects underway between the Engineering Faculty and C-CORE.

The speakers today are Mr. Michael Evans, from CODAR, and Mr. Don Barrick, from NOAA, and Tom Georges from NOAA. I will introduce Mr. Evans, and he will take the ball from there and tell you how he is going to run the show. Mr. Michael Evans is the President of CODAR Technology Incorporated and I had to confess to not knowing what that meant. He tells me it is "Coastal Ocean Dynamics Applications Radar." He was formerly with NOAA in their Sea State Studies Group. Briefly, Tom Georges and Don Barrick are with NOAA. Don is the chief of the Sea State Studies Program Area and Tom runs the Over-the-Horizon Radar Group.

The title of today's presentation as you saw on the notice we circulated, is very long, but it concerns high frequency ground-wave radar for remote measurement of ocean variables. I now introduce Mr. Michael Evans, to make his presentation.

Mr. Evans

This is going to be a somewhat informal presentation. As the gentlemen just said I was previously with NOAA, in fact up until about a year ago from the time I got out of College, the twelve best years of my life.

I started working for Don Barrick in 1975 and our project at the time was to take from essentially the theoretical drawing board the concept of Bragg scattering and HF remote sensing and to in fact develop an applied tool which was somewhat of a first in our research labs. We in fact did this. I was the program manager. I was primarily in charge of developing the hardware and the technology and Don handled the theoretical parts of it. We worked quite well together. Last summer I decided that it was time to leave the government and I was the first one out the door, and formed a corporation.

We're now working with a number of companies including several government agencies, Klaus Hasselmann in West Germany at The Max Planck has bought some hardware and is into the technology and of course Ken Butt has expressed

interest, more than interest as well as several other organizations, so basicall we are at the point of trying to apply this technology. We are now starting to work quite heavily on the wave height directional spectra measuring capabilities of the radar. Basically for measuring surface currents the hardware and technology is essentially complete. It is now a matter of getting it into the oceanographic community and other people. Tom Georges runs the Over-the-Horizon Radar Project as was previously mentioned.

First thing I would like to know is how many people have not seen the CODAR film. We have a film here that was done about three and a half years ago when we first really got the CODAR system going. It is about a twelve minute film an then after that Don Barrick is going to talk about the surface current measuring capabilities of CODAR, then Tom Georges is going to talk about the Over-the-Hori radar project and then Don is going to come back and finish up on wave height directional spectra and then we will get into the questions. I am not going to talk today about the hardware. I will be carrying on these discussions tomorrow with Ken and anybody else interested can sit in. I have to make a few comments on this film. One of the problems we had in this film is that there is some confusion on accuracy and resolution etc. so you need to take some of the comments that are made in the film, as it was an old film, with a grain of salt. This is some very old data but it is fairly impressive and it is also good P.R. for NOAA. I don't know if I mentioned that Don's organization Sea State Studies, is in the National Oceanic and Atmospheric Administration within the Department of Commerce If we could start the film. We will just go from here.

(Film shown called "CODAR, Coastal Ocean Dynamics Application Radar," Office of Public Affairs, NOAA, Boulder, Colorado 80302, 16 mm with sound track, 12 minutes 1978.)

Mr. Evans

Okay, Don Barrick will get into the heart of the subject now.

Dr. Barrick

I will first attempt to go into the system we originally developed, and we feel is operational now, for making surface current measurements and the principles behind it. I understand the audience is quite varied so I don't want to get too deeply into the theoretical stuff nor I hope that I will offend anybody if I cover some basic principles in extremely elementary fashion. I hope you don't feel that I am insulting your intelligence, those of you that see the principle right away, because I understand there maybe people who are hearing what we are doing for the first time.

Okay, surface currents first, then Tom Georges will talk a bit about our skywave radar program and where we are on that, and the principles behind it. Then I will get back into one of the most recent things we are now working on and that is extending the system to measure the wave height directional spectrum and that will cover what we have to say this afternoon.

Surface Currents - We started this about five or six years ago, as I say that part of the program is the furthest along. Why does anybody care about surface currents? Well one of the reasons, we got into it is we saw real need here in that surface currents are very hard to measure. You can't measure them with a current meter because current meters measure currents down maybe six metres below the surface. When you get very close to the surface where the wave action is influencing the current meter, it's bad news. It doesn't work, especially if it is so close to the surface that it is out of the water or swinging back and forth on its mooring. With moored current meters you do a very good job down deep but you don't measure currents near the surface. So there is a need to measure currents near the surface. The only other way of handling that is to track something floating on the surface. Those kinds of experiments where you track drifters tend to be extremely costly and furthermore you only get one, two or three Lagrangian points. In coastal waters where you would like a really detailed structure there isn't anything that works very well so we really saw a need here of something that can measure currents near the surface. Currents near the surface can be considerably different and generally are from currents down deep. Currents a mere six metres or twelve metres below the surface can be totally different than they are at the surface and that is due to the influence of wind on driving waves which in turn gets energy, and momentum flux gets transformed into currents near the surface. In a storm for example or immediately after a storm or under the influence of swell you can find currents near the surface that differ very considerably from currents down deep. So a knowledge of currents deep tells you very little about currents on the surface and the reasons why currents on the surface are important should be probably obvious to a lot of

people. Floating pollutants are one example. Our Coast Guard is interested in surface currents because they get called out on hundreds and hundreds of rescue missions when a small craft is down in the water breaking up. Where that goes is totally a matter of surface currents. Doing environmental studies to understand what's out there before you permit operations in coastal waters is another reason So good technique for measuring surface currents are quite important.

This is a compact picture of the system, we have operated so far for measuring currents in ten different experiments up to this time in different parts of the world from the North Sea to two experiments in Alaska, to an experiment that was just completed last month off North Carolina. The basic system for measuring currents looks like this. We have our computer controlled radar system housed in a trailer although we have used apartments on the beach, helicopters pods, a variety of places, including tents, to put the electronic equipment in. The configuration generally consists of a transmitting antenna and a receiving antenna. The transmitting antenna floods the entire surface out in front of us with illumination. It's for all practical purposes nondirectional. So it is just spraying electromagnetic energy out over the ocean. The receiving antenna that we finally settled on for the last seven or eight experiments consists of four equally spaced elements. We operate at a 25 MHz radar frequency, or our radar wavelength is twelve metres long and this is a departure from what you normally think of as conventional radar. Conventional radar where you see a dish on top of a building spinning around is operating almost three orders of magnitude higher in frequency than we are. Our wavelength is twelve metres. Their wavelength is about the length of your fingernail. So there is a considerable difference in the frequency and in the principles of scatter from the ocean between those two frequencies. It is much simpler at HF ar that is why we chose this region to operate. However, the kind of hardware you deal with is considerably different from microwave. You don't have the spinning dishes. What we have settled on for the receiving antennas were four elements. I won't show the equations, but knowing the voltages at the base of these antennas for each frequency you receive back from the sea echo you can uniquely determine through a direction finding technique the angle of arrival of at least two signals coming from two different directions over 360 degrees. This picture shows you only have water out in front of you over 180 degrees but often times we want to operate on a tower or on an island or on a peninsula where we have water totally surrounding or at least subtending more than 180 degeees. With this sytem after y do your Fourier transform and determine the signals coming at each frequency you can uniquely resolve the direction the signal came from. Now by gating the signal as most radars do, in other words measuring the time difference between when you transmit your pulse and when you receive it, you determine the range or the place the echo came from. So what the radar measures very naturally is echo position in polar coordinates as a function of range and angle, R and θ, if you want to thi of it that way. As you saw in the movie, we take the data from two radar sites ar combine it and then convert to rectangular coordinates to produce a regular grid o vectors like that, straight forward trigonometric transformations. You need two radar systems for currents theoretically speaking because what each measures is th radial component, in other words the component of current pointing back toward the

radar system from a given patch on the ocean. That is only one component of a vector though and in order to get a surface current there are two components, so theoretically you need two radar sites looking at that patch of ocean from two different directions. So almost all our experiments have been done with two radar sites. I will talk about the possibility of cutting one radar site out by using a sort of slick oceanographic technique called the equation of continuity and how you can use that and still get total vector maps with only one radar site. This is a direction finding technique. It is not a phased array. It is a technique I am sure that has been known to the military and other groups for forty to fifty years. The idea of using four antennas and getting the angle, I think is somewhat unique. There is a closed form solution to it, there is no guessing or iterating or anything else to get the angles out of this system. It takes about 4 or 5 lines of FORTRAN code to extract the angles. The angular accuracy is not as with most antennas, it is not a function of the aperture of your antenna. The whole name of the game here at HF was to end up with simple easy to use systems and obviously if you have to go out to the coast and erect a three mile long antenna in order to get a large enough aperture to form a narrow beam nobody's going to be interested in a system like that. We wanted to come up with systems that were simple, where the antennas were simple and you can take them off in a trailer or in a helicopter or whatever, get them set up and be on the air in fifteen minutes and not have to fool around with a lot of ocean front property. So this is a technique. It is not a phased array. It is a direction finding technique. It has its limitations. It works for getting currents. It doesn't work for getting the wave height directional spectrum, so we have gone to another small transportable system for that. But as I say it is not a phased array antenna.

Okay this is the entire system. It is housed in a trailer. Everything is in here: transmitter, receiver, PDP 11/34 minicomputer system that controls the entire operation of the radar and allows you to preprocess and totally process data in the field displaying current vector maps, if you want that kind of real time capability, tape drive which we record all of our data on and take it back, a display which we could use to display either the Doppler spectrum of the signal or limited current vector maps to monitor system operation if we want and the means up here with which the operator communicates with the system. It tells him what he wants. That is the size of it, but actually it has got smaller than that now because we are replacing the PDP 11/34 with a LSI 11/23 microcomputer, which brings the cost down considerably.

The principle of operation for currents can be summarized like this. The mechanism for scattering from this random looking ocean that you see visually is a very ordered process called Bragg scatter. What happens is that you transmit a wave, if you think of it that way, with a wavelength of λ. Ocean waves of all different lengths and periods are out there. The two sets that return the energy to the radar are those sets exactly half the radar wavelength moving toward the radar and away from the radar. Ocean waves, if you know their length have a very

precise velocity or dispersion relationship that defines the velocity that they move at. So you take the echo from a system like this, take a time series of the echo, say over twenty minutes or a half hour and do a Fourier transform of it and look at the energy you get. This is typical of what you would see. You transmit a signal in the frequency domain. This acts as its frequency. This is the spectrum. You would transmit a signal in frequency located in this position. This is your carrier frequency. But what you see in terms of the echo, doesn't come back at your carrier frequency, nor does it come back in a sort of smeared out random looking region around here. It comes back in two discrete positions. This was discovered experimentally some 27 years ago now. A lot of surprise, you look at the random ocean surface and you would expect to see a kind of random looking spectrum but yet you don't. You see two discrete spikes symmetrically placed with respect to the carrier that you transmitted but not necessarily equal to each other in amplitude. Through a sort of deductive process it was determined that if you could measure this frequency shift, if that is really a Doppler effect produced by a moving target you can determine its velocity. If what produced it is an ocean wave train of a given phase velocity, you can work backwards using the oceanographic wave dispersion relationship and determine the wavelength of the ocean waves. Low and behold it turns out to be $\lambda/2$. So that is Bragg scatter. This is the same effect that produces scattering of X-rays and crystals that Bragg discovered at the turn of the century. It is the same thing, in a sophomore physics class that produces a diffraction grating mechanism. It is the same thing that produces a hologram, so what is happening out here, even though the ocean looks random is to first-order, only those ocean waves at half the radar wavelength that scatter in a Bragg type mechanism can return energy toward the radar. One is moving toward the radar, produces a positive shift and the other is moving away from the radar. In reality these are actually components of a continuous ocean wave spectrum that are doing this. But this is a good way to think about it, a continuous spectrum can be broken up into a kind of a Fourier series representation of which only two of those series produce your scale. This is what you see if there is no current present. However, if there is a current present what you see is a shift of these, both in the same direction Δf from their expected positions and this has to be due to the movement of water under the waves. Now again what you see is not scattering from individual water particles. The water particles are undergoing a complicated orbital velocity effect, but what you are scattering from is nearly a perfectly conducting surface that is moving along. If that surface however, is being transported at a given velocity because the entire water mass is being transported at a given velocity, then that will show up in a shift. This shift is small but is very, very measurable with the kinds of accuracies you have with our system. So again you are measuring the movement of the surface, not the individual water particles. It would be the same as if the ocean were a sheet of aluminum foil, and somebody took the edge of that aluminum foil and shook it and started propagating waves down it, even though the surface is not translating, the waves look like

they are translating. If we had a radar system there just like our radar system, it would measure the same thing. It would measure the phase velocity or the velocity of that wave as it moved down the surface. That is what our radars measure. It is not measuring a current, but it does sense the current in the shift of the ocean wave phase velocity from its expected Doppler. Now this is a surface current because you are scattering from ocean waves half the radar wavelength. At 25 MHz, this is twelve metres, therefore we are scattering from six metre waves. There is a hydrodynamic relation that says that six metre long ocean waves (they are relatively short in terms of waves on the open ocean) feel the currents or the bottom, down to a depth of about half a metre, that is about 18 inches. So we are feeling the currents that are transporting the surface water down to a depth of about 18 inches or half a metre. So that is some of the principles.

This is an actual picture of a spectrum. It is very old now. It shows the shift. This is a decimal scale here so again you can see that the dominant echoes, the first-order echoes, stick up two to three orders of magnitude higher than everything else. But there is a weaker set of echoes which we call second-order echoes, that is used to get the wave height directional spectrum which I will talk about later. But the shift is what is used to get the currents.

I have covered the principles of how we get currents out, now the next question anybody asks is that all sounds good in theory but first of all, how well does the system work, how do you establish what its errors are and what physical measurements do you use to support or corroborate your findings. First of all we attempt to do error analysis on the system. We know how the system finds angles. This is an example of some of the error analysis. The method we use to find angles as I indicated is a closed form expression but it is nonlinear. In other words, the angle that you attain out of the system is a function of the signal amplitudes. That is nonlinear and because it is nonlinear attempting to do a straight linear error analysis on a system like this is not possible. So what we have done is extensive Monte Carlo simulations in which we used the actual software that we use to process real data and we put fake signals through it, as you would do with any Monte Carlo process. We generate the sea echo signal which itself is a random variable, coming from two different directions and introduce an omnidirectional noise into the system which at HF it is predominantly external noise. The angular resolution with this system as I indicated is not a function of the antenna aperture width like it is for most radars because we are not using aperture theory. We are using a direction finding technique. But you know inherently that there is some angular limitation. In any direction finding system it is a function of signal to noise ratio, not the aperture size. Now what we are doing here is studying the angular error as a function of signal to noise ratio. In this case it is 20dB, in other words the mean signal is 20dB higher than the mean noise but it is random. We are studying the angular error that we get out of that angle finding routine where we put in one signal coming from 0^{o}, in other words along the diagonal. We can vary that. I am certainly not going to go through all the error analysis but I am going to show just one example. We play around attempting to optimize the process we

are doing. We weight with the signal to noise ratio and threshold which says we favour those angles coming out of this random process that have stronger sign associated with them. That makes sense because when the signals are close to th noise you don't want to use them as you know they are going to produce noisy angular data. This is the angular error we recover. The centre line is for 20d signal to noise ratio as a function of angular error. The centre is the mean and the outer two are the standard deviations. So the mean is very close to 0 which it should be until you get to a sort of unstable region here, near 0^{0} and that is unstable because you are along the diagonal. These studies have taught us a lot of things. They have taught us, for example, that you can get instabilities in the angle finding routine and the way to avoid that is to make your antenna just a little bit smaller, because we are at the point where the distance along the diagonal is half a wavelength and when you work it out, that half wavelength along the diagonal can produce an ambiguity in phase that throws you 0 to 360^{0}. You get phase ambiguity. You shrink the size of the antenna a little bit and you are over that. So there is an angular bias here that we learned about. But the standard deviation here is about 2^{0} - 3^{0} in angle. So for 20dB signal to noise ratio the angular error we get is in the order of 2^{0}. Now this is old stuff, about three years old. We have better angle finding routines. The point here though is that we have done extensive simulations to attempt to determine accuracy of the system. This is one example of many but nobody is really satisfied with that until you actually make comparisons with other measurements in the field.

There are three types of things that we have done, kind of evolved over ten experiments. One is, the first one that came to mind is just a comparison of those current vectors that we see with drifter measurements, Lagrangian measurements averaged over a period of time. One of the limitations of that of course is, you are comparing apples and oranges. You are comparing a Lagrangian drifter measurement to an Eulerian area measurement. The next thing we did is extract the tidal components and compare that with current meters. Now the tidal components should be insensitive to position, whether you are at the surface or down lower. We did that, and found excellent agreement and finally actually used the CODAR as you saw in the movie to calculate trajectories and compare that with something floating on the surface tracked by a boat and I will show you examples of agreements. Here is what you do with the drifter measurement, you basically throw something out, and have a navigation system on a boat like a mini ranger which we had in this case off Alaska. You throw the drifter out. This has plates that extend out down about one metre and a half which is what we feel the radar is measuring current to, so we can get the best possible comparison. You then measure the time and position of the drifter when you put it in the water. About a half an hour later go back and pick it up, measure the time and position, then calculate a mean velocity. This is a standard technique. You then stand of with the boat and let the thing drift for a half hour. This is an extremely expensive way to measure surface currents because a

boat costs $5,000 a day or so. You may get five or six current vectors over a days period but you have to do something like this to convince yourself that the radar is working. We did this off Florida in our first experiment, where we are looking at the Gulf Stream and decided to do the first experiment where we have the most interesting or strong current. The Gulf Stream off Florida as you know around the Miami area, you start from shore and by the time you are around twenty or thirty kilometres, most of the time you have a current of four to five knots, so it is extremely strong, energetic current. What this represents is the surface current velocity magnitude (250 cm/sec is five knots for comparisons) as a function of distance from shore as measured by drifters and as measured by the radar system. The agreement out to this point is about a standard deviation between the two sets of measurements which is less than 10 cm/sec, which is a fifth of a knot accuracy. Beyond this point the comparison is not very good because the drifter kept tipping over and getting entrained in breaking waves and so it wasn't drifting with surface currents any more. But still it is better than two fifths of a knot comparison. That is one type of comparison that we did.

The next thing you try to do is say the surface current is complex. It is made up of wind driven components, it is made up of components due to nonlinear wave wave interaction which is commonly called Stokes drift. The wind stress I just mentioned, it is due to, if you want to think of it that way, a DC component, something that persists for several days and that is due to geostrohpic forces, like the Gulf Stream for example, earth rotation, run-off from rivers and streams and other effects. Finally it is due to tidal components. This is the one we went after next because you know what those tidal components should be. Oceanographers have measured the tidal frequencies in various parts of the world for sixty or seventy years. So we decided to go out after the 24 and the 12 hour components in time series data and look at that, with the system and compare that with current meters. Because that component, if you pull it out of your surface current data should be independent of depth. Actually, it is not 12 and 24. It is close to that. It is 12.3, 24 and 25.9 which are the three most energetic ones. So you do a least squares analysis and pull it out. This is the 12 and 24 hour pulled out and then refit to the data at a time when there wasn't much wind or anything else going on. This is a comparison over time in 24 hours of the components pulled out of the data, the fit, compared with the actual points that were used to determine that fit. From data like this and in comparison with current meters that measure the same thing, doing the same least squares fit to the current meters we determined that the accuracy done in this way over periods of 24 to 36 hours is the order of 5 cm/sec or better.

The first set I showed you was from Florida, the second stuff was from Alaska, and what I will show you now is from the North Sea in Germany. Once you have the tidal components, one nice way of presenting it is a way that the electrical engineers have known for a long time, something resembling a Lissajous pattern where you plot north south, and east west components, along

with the proper phase and trace out an elipse. That way you don't have to actually show the current vector maps every 3 or 6 hours but you show the trace of the vector over a 24 hour period. So, what this radar can do is measure a whole field of these whereas what a current meter measures is one This is an example from the North Sea. Then as I say from that you can compare that with current meters and that's how we establish 5 cm accuracy.

Where some interesting oceanography begins is after you have filtered out the tidal components from the surface current data and plot what is left. This is it. This is back in Alaska again, this is what you saw in the movie. Our radars were here and here, forty kilometres apart. This is what you get after you have filtered out the tidal components. Now what the remainder should be due to is wind, waves and geostrophic effects and run-off. It is with maps like this, that have never been available before, that you can really start to do interesting oceanography.

Trajectories - the final method we have been using lately of comparing and looking at the accuracy and utility of the system is to see what the radar would predict for a trajectory and compare that with what a boat measures in terms of a drifter. This line here with the dashes is a trajectory over an eight hour period, done in a Puget sound area between Canada and United States, the Straits of Juan de Fuca, on the west coast. This is what the radar says the trajectory should be starting at this point and coming this way and this is what the actual drifter measured. Again now, differences may not be necessarily due to the radar, they may also be due to drifter inaccuracies. In general we think we can explain almost all the differences we see here. When they are explained we get agreements over a 24 hour period between the starting point and ending point of radar deduced trajectory and the actual trajectory of a drifter of the order of a kilometre. Now when you think about it over a 24 hour period the kilometre difference corresponds to something like 1 or 2 cm/sec. So that is quite accurate. This is another trajectory, what this shows very interestingly is the effective wind. The solid line again is the actual trajectory of a particle set loose. This line is what you get from the radar if you filter out and only include the tidal components. It says that the particle would have come along here around shore and gone like that. However, when you take the whole surface current as measured by the radar which includes wind effects for this very same record, they track each other very well. So what is does is it permits you to pull out and study the effects of the various components that drive the surface currents on how they will actually transport a body floating on the surface.

Summary of some of the trajectory comparisons. I already covered the first one. Better that one kilometre after 24 hours. Differences we have seen are always explained by interference and other things that we see in that data.

That covers my talk. Two other things I might mention, that suddenly occurred to me. I noticed in the brochure I received that there is some interest here in tsunami detection. We suggested and proposed this 2 or 3 years ago in the literature as a tsunami detection and warning technique. A tsunami as you know is produced by an earthquake. When an earthquake happens, at least in our country, they go into what's called a tsunami watch. When there's first evidence of a wave that hits shore, you go into a tsunami warning. Well right now at least in our country we switch to a tsunami warning when some part of the coast gets hit by the onslaught of the first wave and usually the way that that is sensed is through tidal gauges. Generally what happens is that it just totally rips out two or three tidal gauges and you say, Hey! Its time to switch to a watch, if anybody is alive at the coast at that point, so it may give people a little bit down the coast a warning but it does very little if you are the first place to be hit. With a system like this you are measuring the surface currents. Now a tidal wave or a tsunami as it moves in closer is setting up a field of orbital velocity on the surface, you can sense that. I've calculated the magnitude of the velocity produced by an average tsunami and it can be seen with a system like this. It is 20 or 30 cm/sec as that tsunami moves into shallower water up on the continental shelf. For the United States, of course, the continental shelf depth varies considerably. The East Coast is quite shallow, the Gulf of Mexico is extremely shallow, and on the West Coast it falls off very quickly. Calculations for the West Coast show that you could get forty minutes warning with a system like this. For the East Coast it is about an hour. Now I don't think you would build a system like this specifically for tsunami warning, but if you had it operating for currents you would certainly turn it on when an earthquake occurred somewhere. You would get evidence of that right away and have an added use for the system in terms of switching to a mode that can then look for that characteristic pattern of a tsunami wave, estimate its amplitude as quickly as possible and get the warning out. There is a need for systems like this.

The other interesting thing, (or application) is the use of one radar station instead of two to measure surface currents. There is a principle, conservation of water or the continuity equation, that says $\nabla.V$ for an incompressible fluid equals zero. If you write in terms of polar coordinates, you end up with something like

$$\frac{dV_r}{dr} + \frac{1}{r}\frac{dV_\theta}{d_\theta} + \frac{dVz}{dz} = 0$$

This is written in polar coordinates which is a natural coordinate system of the radar. In general, vertical flow in the ocean is very small and so are vertical gradients in the ocean. If this term is zero, the radar measures the radial component here. That says that you can solve for the remaining component to this differential equation at the surface of current velocity V_θ by a partial differential equation if you have a proper starting boundary condition. A good proper starting boundary condition is that flow normal to the coast is zero - if it isn't

the coast is soon underwater! So that works and you can use this with only one radar site to establish complete current vectors maps. Now there are a lot of caveats, and I don't have time to go into them, in doing this. We have tried th and it works and we want to try to understand more about it because after all if you can eliminate one radar system you can cut the cost, and logistics and every thing associated with an experiment by far more than a factor of two. With this I will get out of the currents and let Tom talk a bit about the skywave radar an the use of it for ocean surface measurements.

Dr. Georges At the risk of totally confusing you, I am going to talk a little bit about a completely different application of HF radar. The only connection between this and what Don and Mike have been talking about is that they are both derived from the same mathematical theory of sea scattering that was developed by Don and other people.

I need to tell you that this is a joint project between NOAA and SRI International in California. It is called the Skywave Sea State Radar Project. SRI supplies the radar system, and some analysis, and we supply some propagation analysis and signal processing strategies.

So what is a skywave radar? Basically it is an HF radar system like Don and Mike were talking about. The particular system that we have been using employs two stations out on the coast of California. Here (figure A1) is San Francisco. There is a transmitting facility and a receiving facility 185 km apart, because it is a CW radar system and not a pulse radar system. You can have a pulse radar system with the two facilities at the same place. This happens to be a CW system, so it requires a separation. The transmitter radiates an HF signal that bounces off the ionosphere and illuminates a patch on the sea whose location can be scanned in azimuth and range by steering the beams of the transmitting antenna and the receiving antenna. The signal scatters from the sea; most of it goes off this way but some small amount of it comes back by a similar ionospheric path and is received at a receiving station here and processed for the sea state information out here. The difference between this kind of system and the surface-wave system is that it is able to scan a much larger area of ocean. It illuminates a very small spot, a few kilometers square but it can scan 4,000,000 km^2 of sea, in the North Pacific Ocean in this case. The price you pay for this thousand-fold increase in coverage area compared with the surface-wave radar is two-fold. One is that you have to contend with reflection from the ionosphere, which is really the problem in using a skywave radar. What you would like is a perfect mirror, in which case you would be able to see an undistorted picture of the sea echo. What you really have is undulating, time-varying, random-like mirror. You have to deal with the distortion that the ionospheric reflection causes. The second disadvantage of this kind of system is that you need large, permanent, expensive facilities.

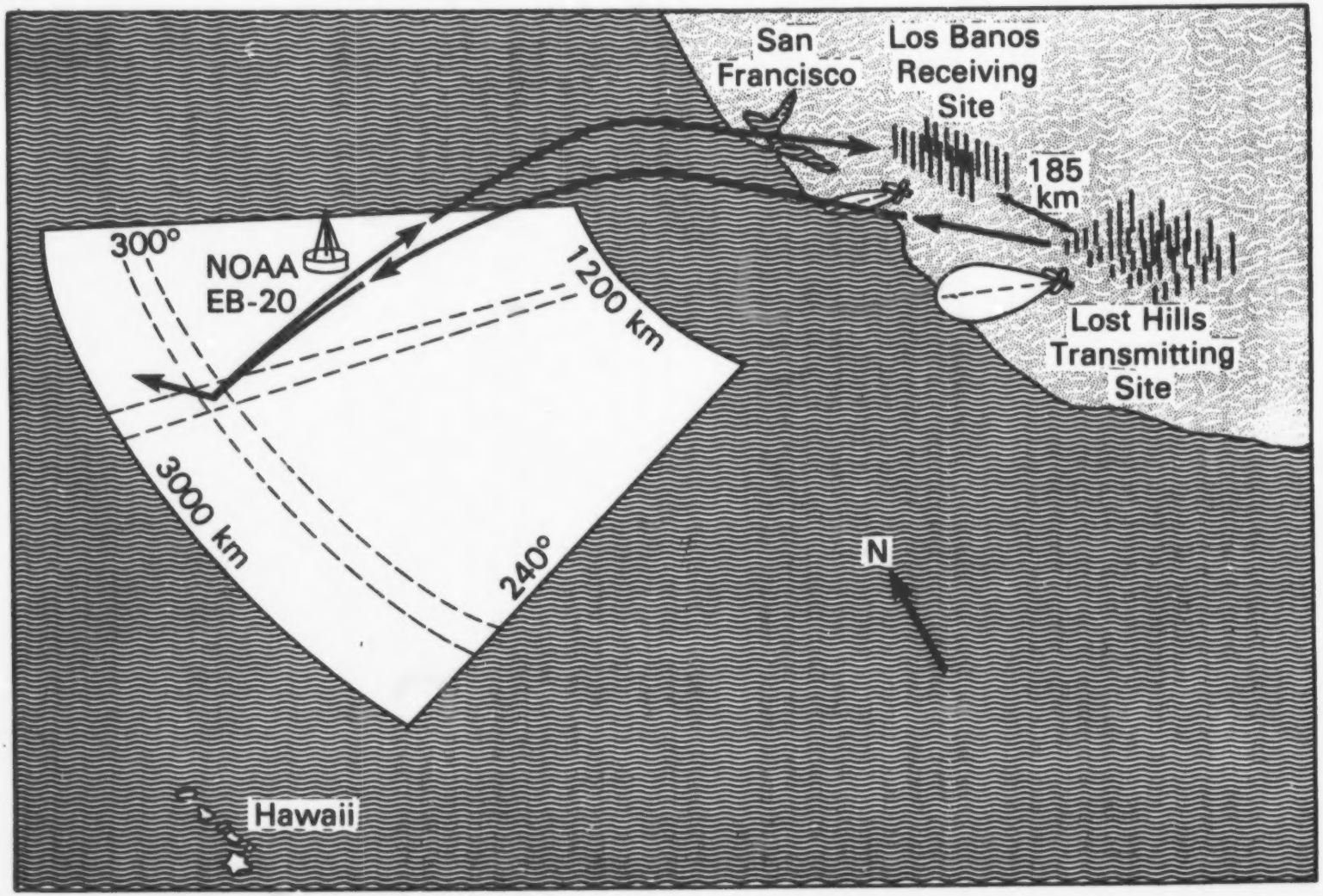


Figure A1. SRI, Wide Aperature Research Facility (WARF). [Courtesy of NOAA Wave Propagation Laboratory]

I will show what kind of facility you need later.

Here (figure A2) is an example of a skywave sea echo spectrum with the two Bragg lines, the same two Bragg lines that Don talked about. Here also is the same second-order continuum, which is caused by double scattering from the sea and from wave-wave interaction of several ocean waves on the sea surface. I am going to talk about the structure of this backscatter Doppler spectrum in more detail as we go along. One more point to mention here is some of our ground truth out in this area. NOAA EB20, which died a few weeks ago, but until then we could use as a measure of ground truth of the various things that we can measure out here. Unfortunately, there is only one of them in the whole scan sector, so we can do a calibration at one point, but we don't have ground truth over the whole scan sector.

Just to give you an idea of the kind of coverage that is possible with skywave radar, here (figure A3) are two hypothetical locations of skywave radars in the United States. One, I believe, is in Idaho but it doesn't exist. If it did exist, it could cover, with perhaps two antenna arrays the entire waters off the west coast. Similarly another radar in Tennessee, or Kentucky perhaps, could cover the entire Gulf Coast and Eastern Coast, perhaps for monitoring tropical storms that approach the East Coast. So, just to give you an idea for the scale of things that are possible with the skywave radar, this is kind of the end result of what could happen operationally in terms of the actual services it could provide.

Here (figure A4) we have a kind of a glorified view of a skywave station with a transmitting station here radiating out to the sea and recieving the waves coming back here. This is a receiving station and a processing centre. Here's a fellow sitting there doing all the propagation analysis in real-time and looking at weather chart displays on the scopes and transmitting processed data in real time to various weather service offices who have need for things like maps of surface wind speed, the rms wave height, the scalar ocean wave spectrum and maps of wind direction fields. For example, such a radar can do real-time tracking of tropical storms as they approach the coastline. This is partly in the future but partly a capability that exists right now. For example, we can transmit in real time this information right here. We have actually done so in cooperation with the National Weather Service. These things over here are more in the future but only require an operational program to implement.

Now a little bit of theory. What can we actually measure with the skywave radar?

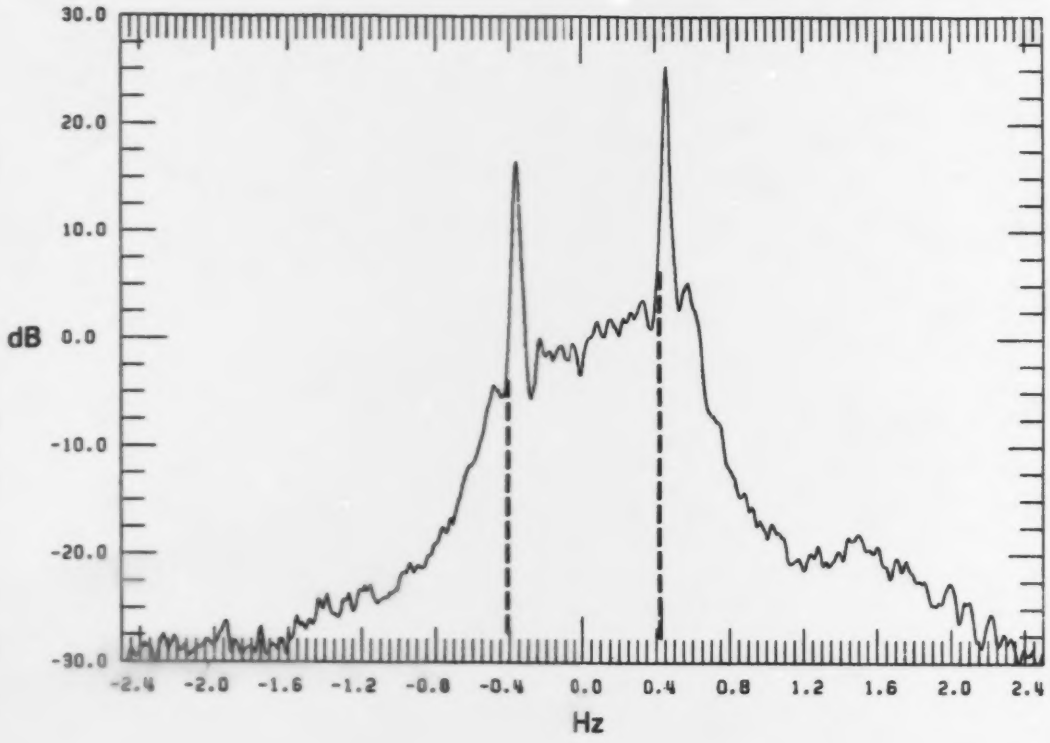


Figure A2 WARF Skywave Sea-Echo Specturm, 2 June 1977, 1819z; 12.0 millisecond range; 0.5 deg. beam width; frequency = 16.3 MH_z, 512 point (102 second) spectra [courtesy of NOAA].

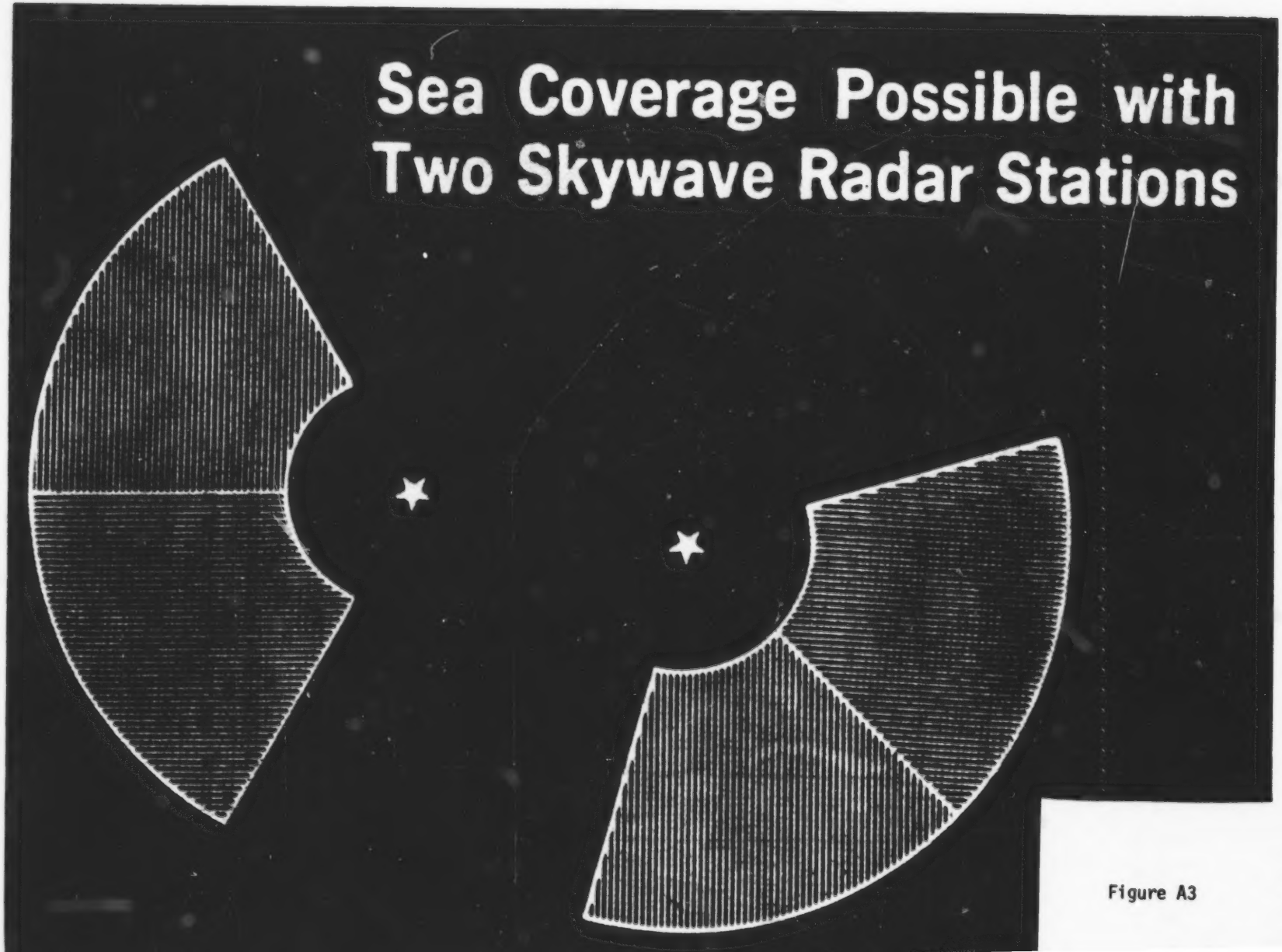


Figure A3

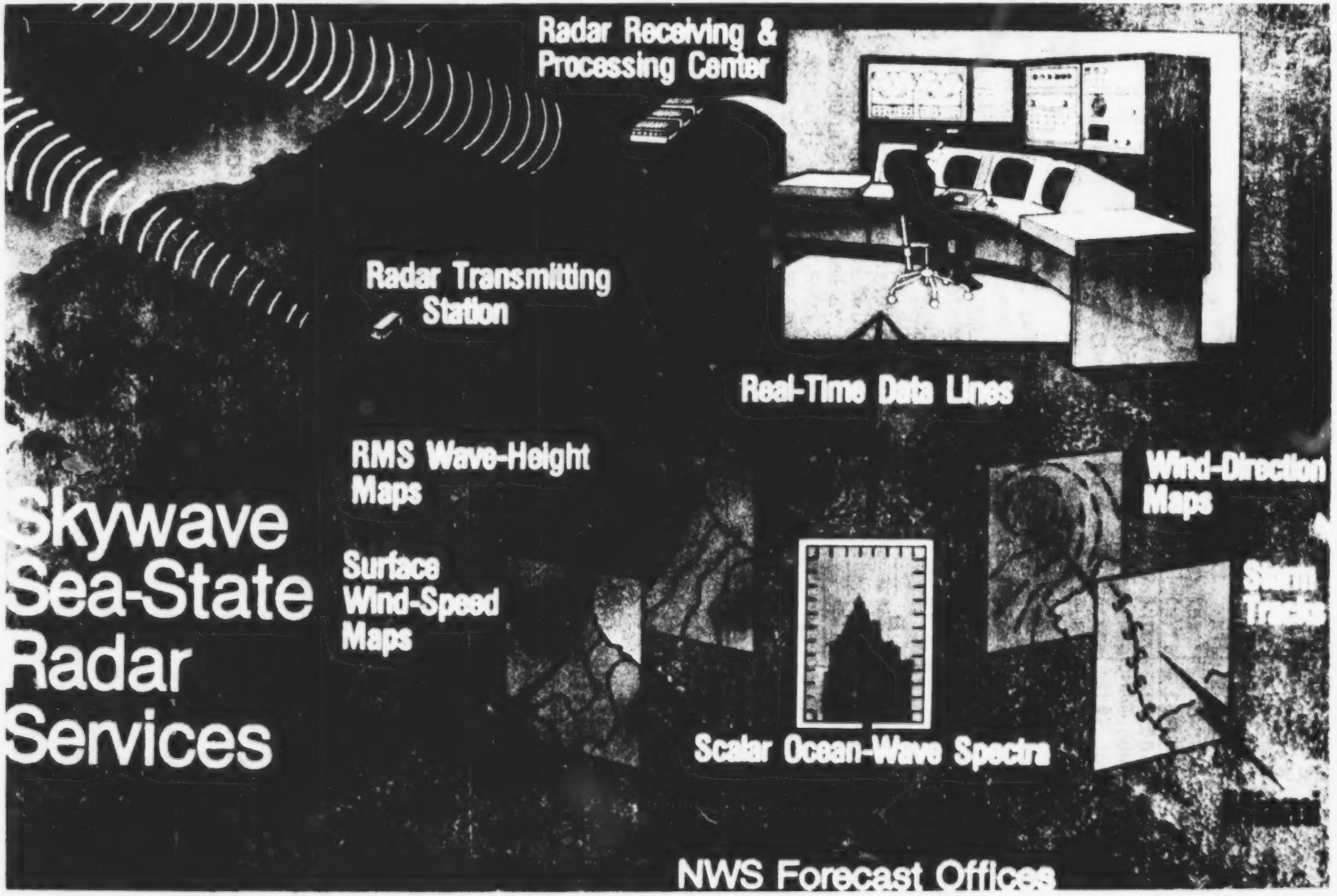
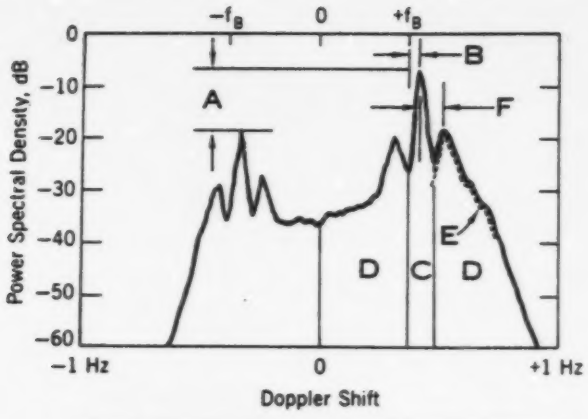

Radar Receiving &
Processing Center
Radar Transmitting
Station
Real-Time Data Lines
RMS Wave-Height
Maps
Wind-Direction
Maps
Skywave
Sea-State
Radar
Services
Surface
Wind-Speed
Maps
Scalar Ocean-Wave Spectra
NWS Forecast Offices

Figure A4.



A	—	Short wind-wave direction (surface wind direction).
B	—	Surface current.
D/C	—	Rms wave height.
E	—	Scalar ocean-wave spectrum.
F	—	Frequency of dominant ocean wave.

This (figure A5) is a stylized picture of the Doppler spectrum received by a HF radar.

This is where all the information is. If you send out a radar wave, what comes back is a signal spread in frequency over a spectrum about 1 Hz wide at most HF frequencies. All the information that you get about the sea is in this so-called Doppler spectrum. We recognize the two so-called first-order or Bragg scatter lines. We recognize some second-order structure represented by these two peaks and the continuum that's filled in between the two first-order lines. I'll just go through very quickly to show you what you can get from the Doppler sectrum. "A" is the ratio of power in the two Bragg lines. This tells you the relative strength of the scatter from the waves coming toward you with positive Doppler shift and the-scattering strength from the waves going away from you. What this tells you is the relative strength of these two waves, and if you have a model for how the wind generates short waves on the ocean you can infer the surface wind direction from the ratio of those two echoes. For example, if the ratio is unity, they have the same strength, then you can infer that the wind is blowing across the radial from the radar. There is a left right ambiguity built into this measurement which can be resolved with various tricks, knowing something about the circulation in advance.

The surface-current measurement "B" as Don described, is the shift from symmetry about zero. In other words, without currents these two Bragg lines are symmetrically disposed about zero Doppler shift. With currents, these two lines are shifted uniformally to the left or to the right. The amount of that shift, (B) is the direct measure of the radial current component. The rms wave height which is something that we are very interested in from the skywave point of view is roughly indicated by the ratio of the power in the second-order part of the spectrum indicated by (D) to the total power in the first-order part of the spectrum by (C) with a little bit of license here because of a logarithmic scale. If you measure the ratio of second-order to first-order power you get a self-calibrating measure of the rms wave height. It doesn't require measurement of absolute scattering cross-section at all. All you have to measure is the ratio of (D) to (C) and go through a little power law formula or some other simple formulas and you can get rms wave height from all the ocean waves in the illuminated cell.

(E) is a rough indicator of the shape of the ocean wave spectrum. Just crudely speaking, you can think of the shape of these four second-order sidebands as roughly a picture of the scalar ocean wave spectrum on the sea surface. Strictly speaking, you have to do a full mathematical inversion of all four sidebands to get an accurate measure of the scalar ocean wave spectrum, but crudely speaking, you can think of this dotted line as roughly indicating the shape of the spectrum. For example, the separation of the second-order peak from the first-order Bragg line as denoted by (F) is a pretty good measure of the frequency of the dominant ocean wave on the surface of the sea. So this a whole collection of things that you can get by measuring different parameters of this Doppler spectrum from the sea.

One particular thing that we are very interested in and that we have working very hard to get accurately with the skywave radar is the rms wave height. Here (figure not available) is a theoretically computed Doppler spectrum using a model for three different wave heights, and you can see what is going on here as the wave height increases. The first-order contribution to the spectrum remains, it is normalized so that these are all the same. You can see that the second-order contribution increases as you go on from each $h_{1/3}$ of 4.2 ft. to 10 ft. to the largest one. As the wave height increases the second-order contribution gets larger and larger relative to the first-order contribution. The trick in measuring wave height is to be able to identify the second-order part of the spectrum from the sea echo, distinguish it from the first-order part, measure the relative powers and then you have rms wave height. This is what we spent a lot of energy trying to do with the skywave radar.

This (figure A2) shows an actual skywave sea-echo spectrum made with the WARF, the Wide-Aperature Research Facility operated by SRI that I mentioned earlier. This is quite a high quality spectrum obtained at a range of about 1600 km out on the North Pacific. You can see all the features that I have been talking

about: The first-order Bragg lines, the second-order continuum, frequency range of -2½ to +2½ hertz, dynamic range of 60 dB top to bottom, so it is a logarithmi scale. This is what you would like to have all the time. If you had this kind of spectrum you would have no trouble measuring wave height. Notice one thing though, the spectrum is shifted in the manner that I described as indicating currents. However, this isn't necessarily caused by currents; this can also be caused by motion of the ionosphere. If the reflecting ionospheric layer is moving up or down it could cause a shift to left or right of the whole spectrum in a way that is exactly the same as the shift produced by currents. This is why you can't usually measure surface currents with a skywave radar. The effects of the ionosphere are almost identical to the effects produced by currents. So you need a zero-Doppler reference. If there was an island out there, for example, there would be a spike in the middle of this spectrum, and if it was exactly at zero Doppler you would know that this shift is caused by ocean currents. If that island spike were shifted by the same amount as the Bragg lines, then you would know that the shift was caused by the ionosphere. In general it is a mixture of the two. In the absence of the zero-Doppler reference, you can't tell which. In general, you can measure currents only along coastlines, near islands, near platforms, near anything that gives you an echo that you know is zero-Doppler.

The problem that we have in practice is that most of the time the sea-echo spectrum does not look like this. What happens a lot of the time is that the spectra are much more messy. Here are some averaged spectra (figure not availabl That previous one was an average of about 40 or so. That reduces the amount of fluctuation in the spectrum. Here are some examples of spectra obtained under different ionospheric conditions. Here are the two Bragg lines again, in each case left/right, left/right. These are four spectra. This one is obtained under good ionospheric conditions that produces a sharp spectrum, so the two Bragg line are very sharp and if you expanded this out you would see the second-order structure and clearly delineate the two. A lot of the time you see echoes that look like this. This looks like you are seeing a double version of this. There are two Bragg peaks, two of everything superimposed but shifted. This is caused by ionospheric multipath. The radar is illuminating the sea by way of two different paths through the ionosphere. Each path has its own Doppler shift because of motions in the ionosphere so the resulting sea-echo spectrum is two of them, supe imposed and shifted. Now, as you can imagine, there are situations where we have larger and larger numbers of paths through the ionosphere for various reasons, which result in multiple versions of the spectrum superimposed on each other. Then there is the extreme case where you have severe broadening of the spectrum due to large numbers of paths through the ionosphere. In each of these cases, you can still measure the ratio of the two Bragg lines to get things like the win direction, and this shows that the ionospheric distortion doesn't affect that par ticular measurement at all. So you can still measure the total power here and here and this broadening doesn't affect that measure very much. On the other han if you are trying to measure wave height you need to distinguish between the ener

in the first-order part of the spectrum which is in this principal peak and the energy in the second-order sidebands. You can only do that here, perhaps if you are clever about removing the two paths. It is out of the question here. So this kind of ionospheric distortion prevents you from making accurate wave height measurements.

So what do we do about it? That is the question that our team has been worrying about for the last three or four years. What do you do about the ionospheric contamination of the sea echo spectrum? Can you remove it? Can you avoid it? Can you process it out? Can you do anything with your radar that will make it go away? Well one of the things we did was to try to figure out what causes it - try to manufacture a model for what the ionosphere does to the sea-echo spectrum. One thing we came up with is that as the radar illuminates the sea by reflecting from the ionosphere, one way that the ionosphere behaves, among others, is to cause a multiple number of ray paths, (figure A6) as though the surface of the ionosphere looked like a ripply perfect reflecting surface, something like the surface of a swimming pool when you see sun glints of it. Each of these glints on the surface of the ionosphere causes a distinct ray path, each with its own distinct Doppler spectrum. One thing we decided is that the smaller you make this radar beam the fewer of these glints you are going to illuminate. That is one thing you can do to your radar to get better quality sea spectra, reduce the beamwidth, and thus reduce the size of the ionospheric patch that you are illuminating.

Next, I formulated a kind of a strategy for dealing with the ionosphere contamination. It seemed like a very large, multi-faceted problem. One approach (figure A7) was to model the contamination process so we could have a quanitative and a conceptual basis for doing things to optimize how the radar deals with a contamination and to develop signal-processing parameters that were attuned to our physical model of what was happening. Another thing we realized was that you have to have ways to look at what the ionosphere is doing right now over the radar path in order to do frequency management effectively. We figured out several different ways to develop real-time ionospheric diagnostic tools that acknowledge that short-term ionospheric dynamics is really unpredictable. There is no way to have synoptic types of models that tell what the small-scale structure of the ionosphere is doing right now. The other part of the strategy for dealing with contamination is to develop signal-processing strategies for removing and avoiding the contamination. I won't be able to go into the signal-processing very much at all. For people who are interested we can talk about it in detail later, but the whole signal-processing subject is about a two to three hour lecture in itself. The last part of the strategy is to make spot measurements where you have in-situ sensors to compare and verify that these other three things are working. As I said before, the final test of the usefulness of a system like this is to put it into an operational context and see if it actually makes the kind of measurements that real users want.

This (figure A8) is just a snapshot of the kind of ionospheric diagnostics that we use. I am going to go over them very quickly. This is a conventional sweep-frequency ionogram taken directly over the radar. It is a picture of the travel

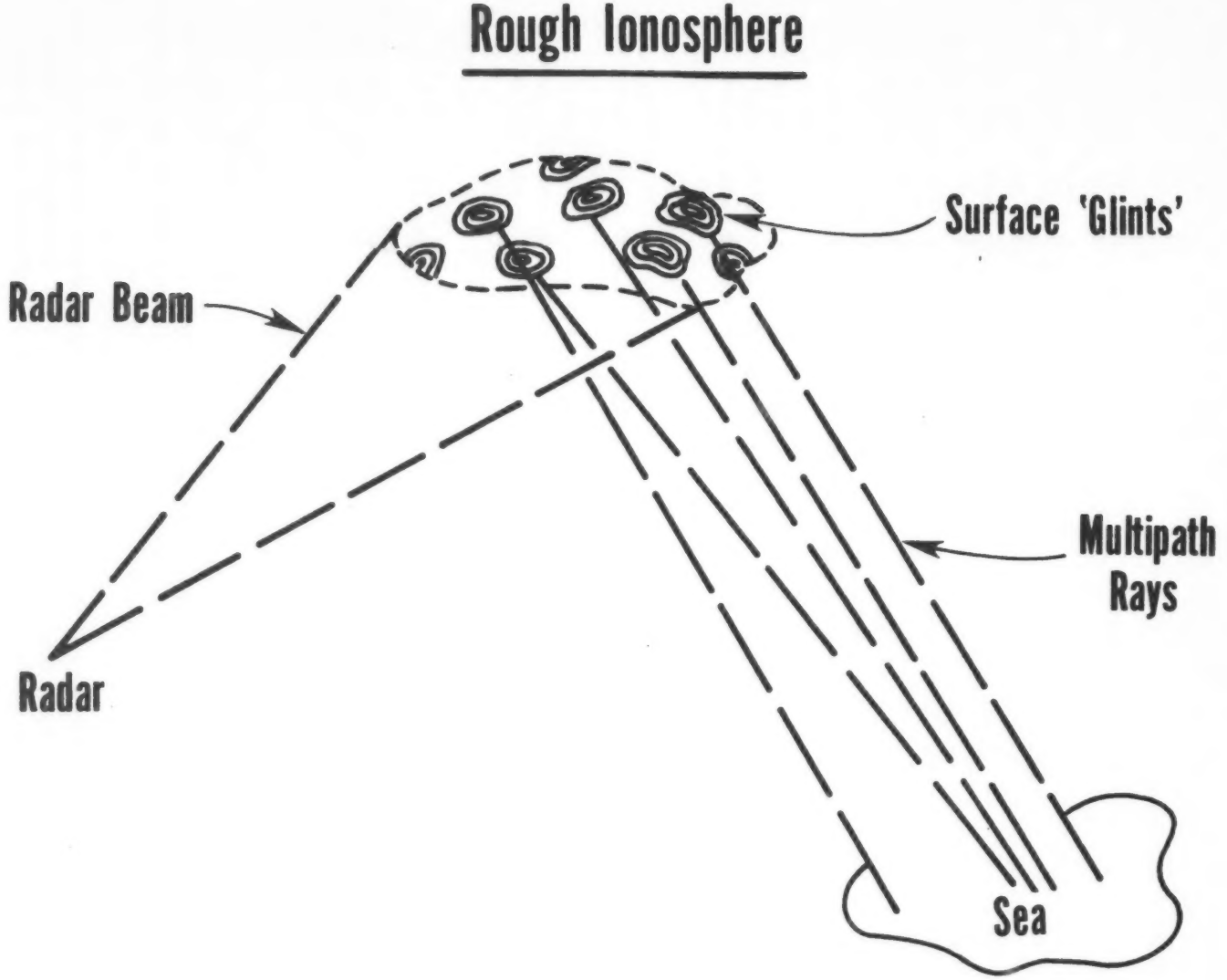


Figure A6. Ionospheric multipath caused by "surface glints".

STRATEGY FOR DEALING WITH IONOSPHERIC CONTAMINATION

- **Model the contamination process**
  - **— a quantitative and conceptual basis for optimizing radar and signal-processing parameters**
- **Develop real-time ionosphere-diagnostic tools**
  - **— acknowledging that short-term ionospheric dynamics is unpredictable**
- **Develop an automatic signal-processing sequence**
  - **— first for measuring rms wave height, then the scalar ocean-wave spectrum**
- **Verify spot radar measurements by comparing with in-situ sensors**
- **Assess the operational potential of skywave radar, accounting for realistic ionospheric variations and the needs of potential users**

Figure A7. [Courtesy of NOAA]

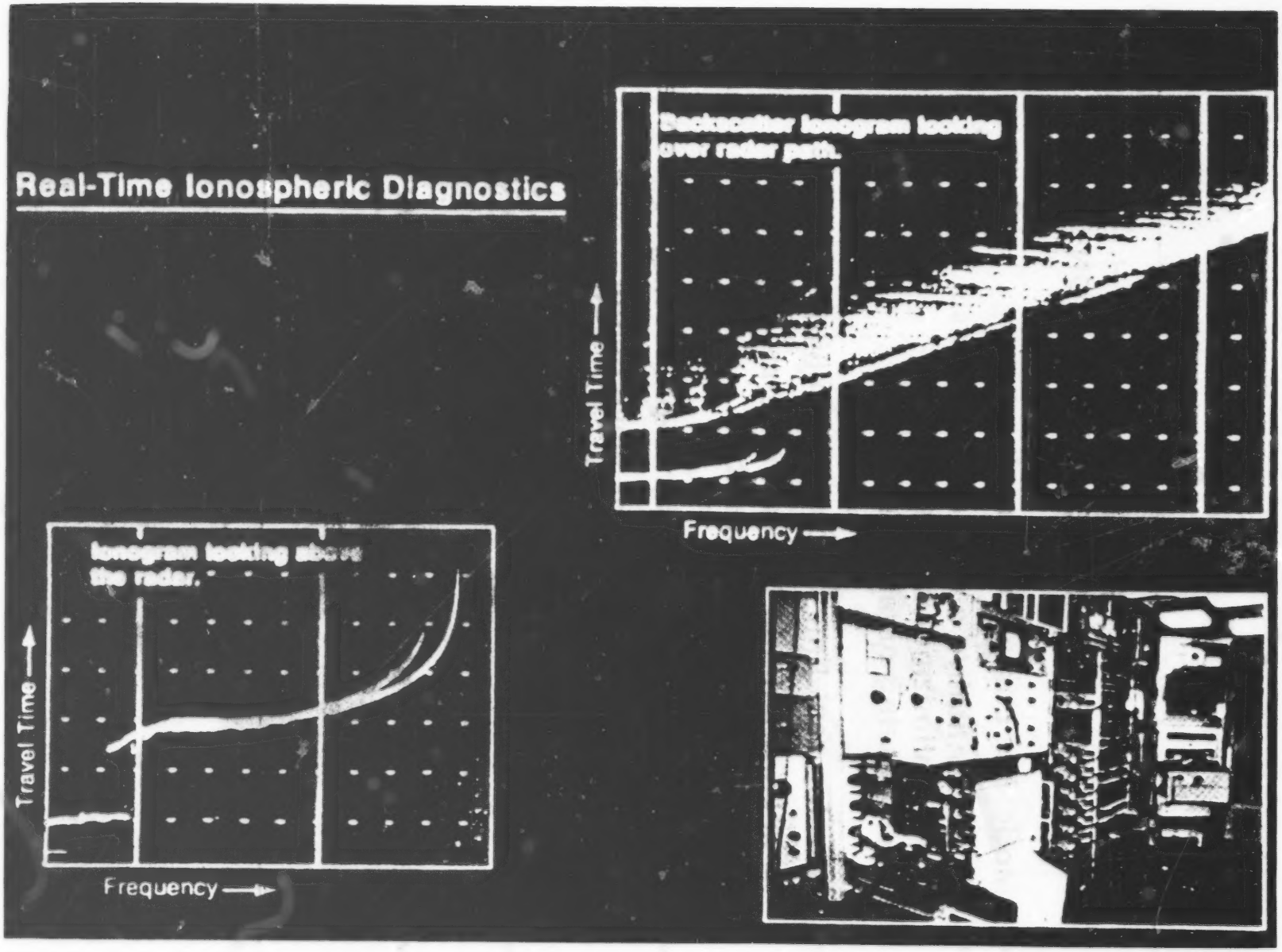


Figure A8 - Real-time ionospheric diagnotics showing conventional sweep-frequency vertical and oblique ionograms and

time versus the radio frequency of a wave that is sent up into the ionosphere and echoed back, and this is a well known conventional picture of the structure of the ionosphere or could be translated into one. This is the same kind of ionogram (travel time versus frequency) looking out over the radar path itself so this is the energy returning from the ground or from the sea, all the energy within the radar beam, as a function of frequency. You can see that as you increase your frequency your skip distance goes out with frequency and you can, using both of these things together in a complicated way that I don't have time to describe, choose an optimum frequency that avoids some of the multiple-path propagation through the ionosphere. At the SRI radar we have a machine that spits these two things out every five minutes and they do change from five-minute sample to five-minute sample. So you really do need to keep looking at them while you are operating the radar.

Another signal-processing strategy has to do with temporal changes in the ionosphere. This (figure A9) shows two Doppler spectra that are averages of 84 Doppler spectra obtained a couple of years ago. They are identical in every way except that this one was obtained seven minutes later than this one. So it shows that if you are operating a radar you can sit there and get a spectrum that looks like this at one time and a spectrum that looks like this just a short time later, just caused by changes in the ionosphere. If you are interested in measuring the wave height, which as you recall requires you to distinguish the second-order from the first-order part of the spectrum, you will see that you can make that distinction here because you can see little peaks and nulls that indicate the delineation between second-order and first-order energy. You can see that distinction here. You can't see it here. What this shows you is that a certain amount of patience is called for in dealing with the ionosphere. So here (figure A10) is a very simplified picture of our strategy for dealing with the variation of the ionosphere: We have a search strategy that we set up to measure wave height at a grid of points within our scan sector and we let the radar run. We have mechanisms that are set up to tell us how good the echo is in real time, while the radar is running. It is telling us from minute to minute how suitable the sea echoes that we are getting are for wave-height analysis. If they are suitable, it sends it to a processor that computes the wave height. If it is not, it tells us to keep searching or to keep sitting at that one point.

Now I'm going to give you a few examples of what the skywave system at California can do. This radar is situated here (figure A11). It can look both eastward and westward covering this area or this area. One hop ionospheric propagation probably limits it to about this region here and a similar size region that includes the western Gulf of Mexico on this side. The beamwidth of the antenna is indicated by the width of this dotted line, so it is about a half degree, nominally, at 15 MHz. I am going to be describing some measurements out here in the North Pacific and then I am going to be showing you some more measurements

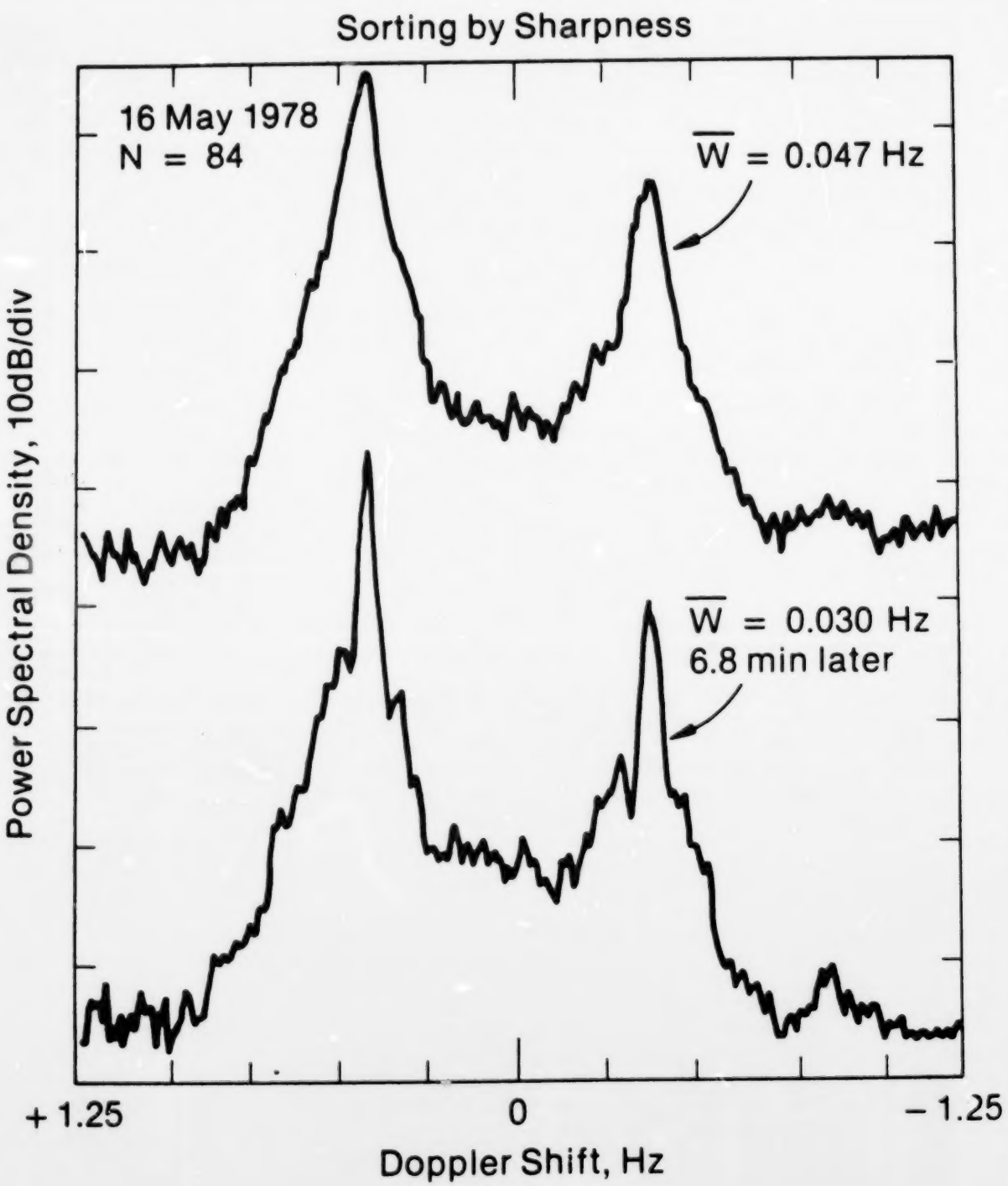


Figure A9. A processing strategy that relies on temporal variation of the ionosphere to eventually provide an acceptable path. Sorting is based on spectrum sharpness.

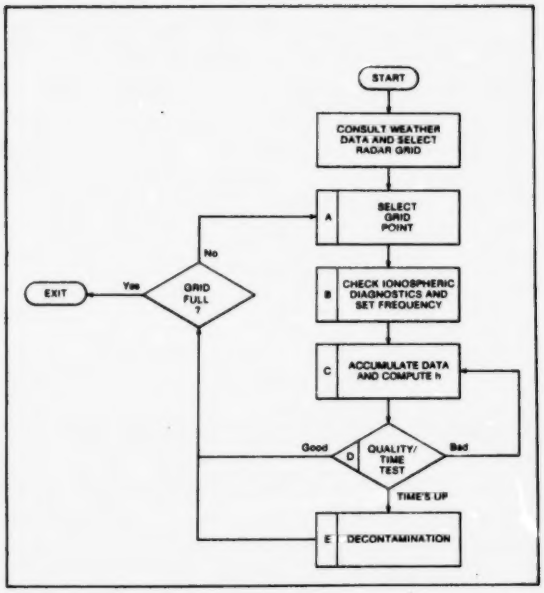


Figure A10. Waveheight Processing Strategy. [Courtesy of NOAA].

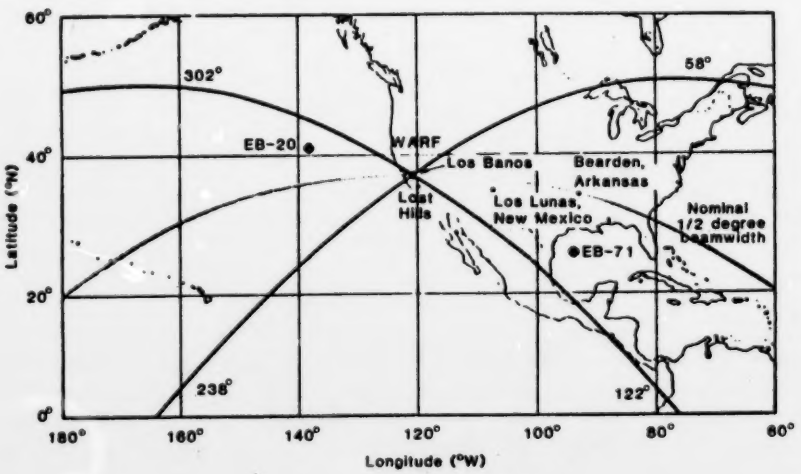


Figure A11. Coverage area of the WARF HF skywave radar. All Anita measurements were made west of 88°W in the Gulf of Mexico [Courtesy of NOAA].

down here in the Gulf of Mexico.

Before I do that, here are some pictures of the actual radar setup. As I said, it is permanent. You can't carry this around in a stationwagon. This is one of two transmitting antennas. This is the one that looks toward the West. You can't see the structure of it but it is an array of vertical log periodic antennas. These are just supports. The heart of the WAKF system is a 2½-km-long array of twin-whip antennas (figure A12). This produces an effective receiving beamwidth of half a degree. It is scanable, $\pm$ 32° in azimuth and by switching the relative phasing of these two rows of elements, it can look either to the East or to the West. This is the operating console of the radar. We get real-time displays on this scope here and at the same time we get hard copy plots of what is on the display here. I will show you some samples of the real-time displays in a minute. All the rest of it is computer equipment: discs, tape drives and things like that.

This is an example of a wind direction map, each vector on here is a wind direction, computed with the radar. This is in the middle of a hurricane in the Gulf of Mexico. This (figure A13) just shows how you can map the wind direction. The magnitudes of the vectors don't mean anything. It is just the direction that means something. This shows that you can map the wind direction of the circulation of a hurricane. You can also deduce the location of the centre of the hurricane. It now takes about 10 minutes to make one of those maps in real time and you can track the centre as it moves along very readily in this way.

Here (figure A14) is a set of wave-height measurements made on another hurricane, Hurricane Anita, in a one-hour period. These are three different measurements of wave height compared and each one is subject to error, so you shouldn't regard any one as being ground truth but nevertheless they do compare pretty well. The contours are derived from a hindcast of the wave heights in the region. The open circles are derived from a time sequence of buoy measurements of wave height at slightly different times as the hurricane passed through. So this just involves a space-time transformation, as the hurricane passed through. These five solid dots indicate the rms wave heights in feet. You can see that the numbers compare pretty favourably in wave height.

The ability of the radar to track a hurricane is shown here (figure A15). This is the Gulf of Mexico and this is Louisiana, Texas, and Mexico. This is the Gulf Coast and this is the track of hurricane Anita. The solid line is the National Hurricane Centre's best track and these solid dots are the estimated positions using the radar. The mean error or the rms error is something like 18 or 19 km and there are 17 estimates from the radar on there.

This (figure A16) is an experiment that we have done out in the North Pacific near EB20 during the passage of a cold front past the buoy which showed a rapid increase in wave height and rapid changes in sea state. Note the three rectangles here. This is kind of busy, so I will explain it in pieces. Look at this piece first. The three rectangles show three of several cells interrogated by the radar and these are the respective samples of Doppler spectra from these three points.

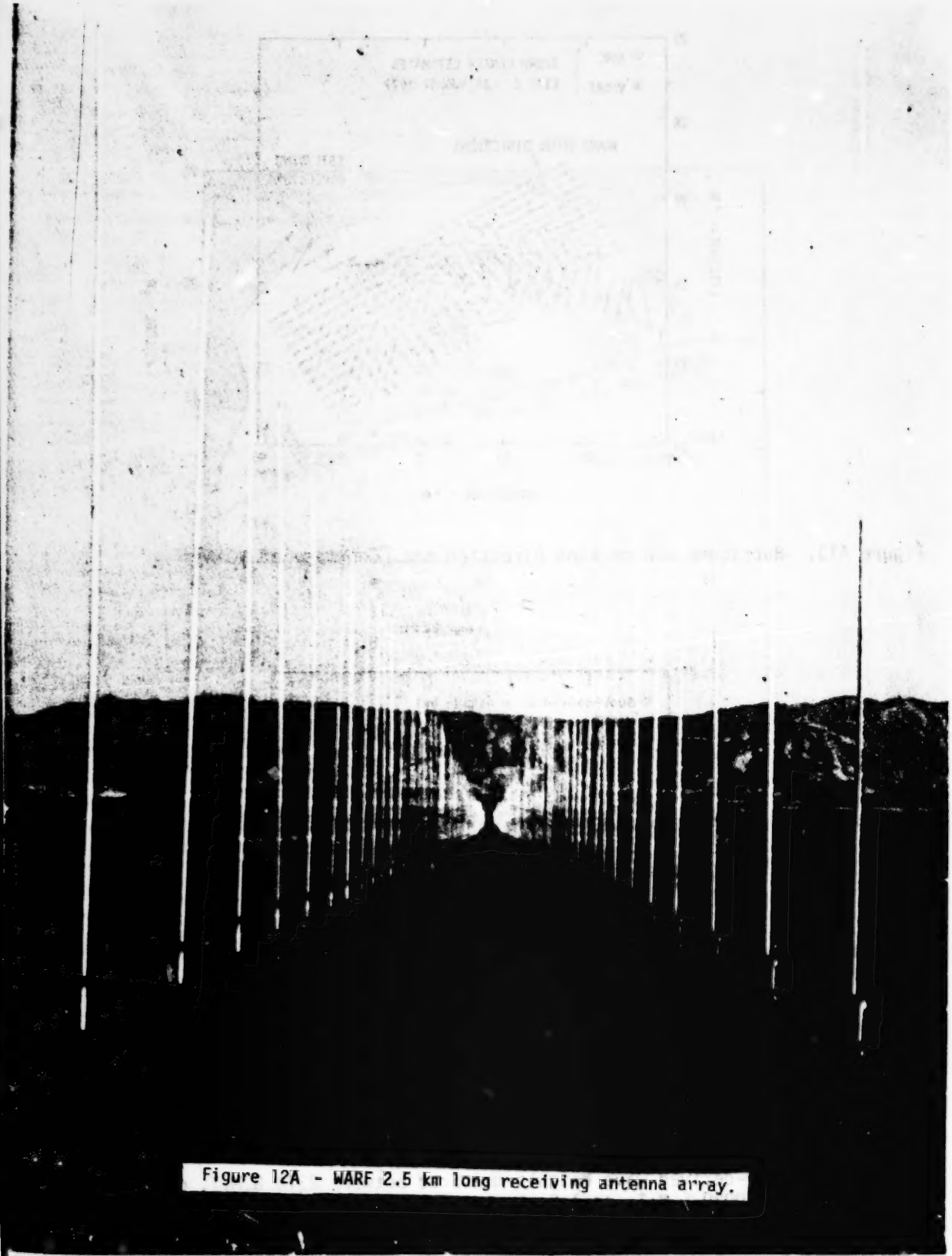


Figure 12A - WARF 2.5 km long receiving antenna array.

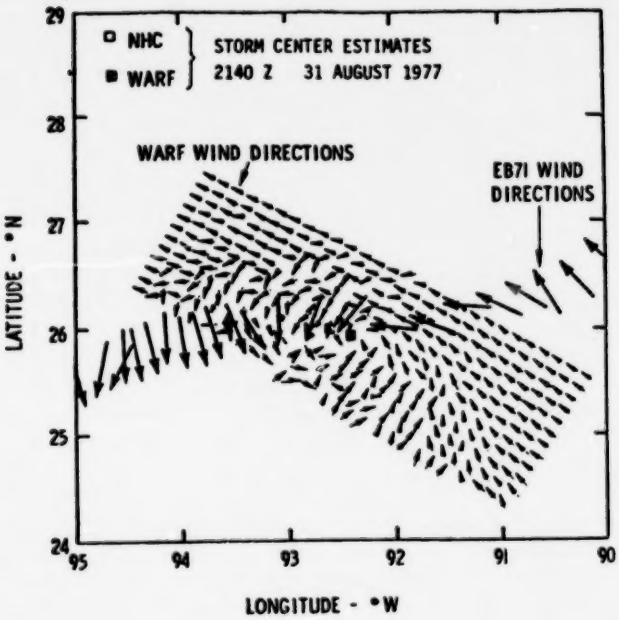


Figure A13. Hurricane centre wind direction map [Courtesy of NOAA]

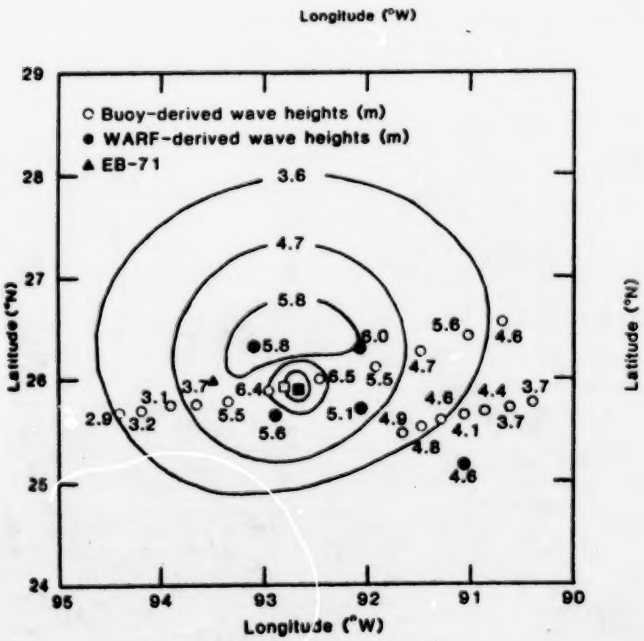


Figure A14. WARF-derived wave heights measured between 2314 G.M.T. on 31 August 1977 and 0020 G.M.T. on 1 September 1977, and EB-04 and EB-71 arrived significant wave heights measured between 0600 G.M.T. on 31 August 1977 and 1800 G.M.T. on 1 September 1977. [Courtesy of NOAA]

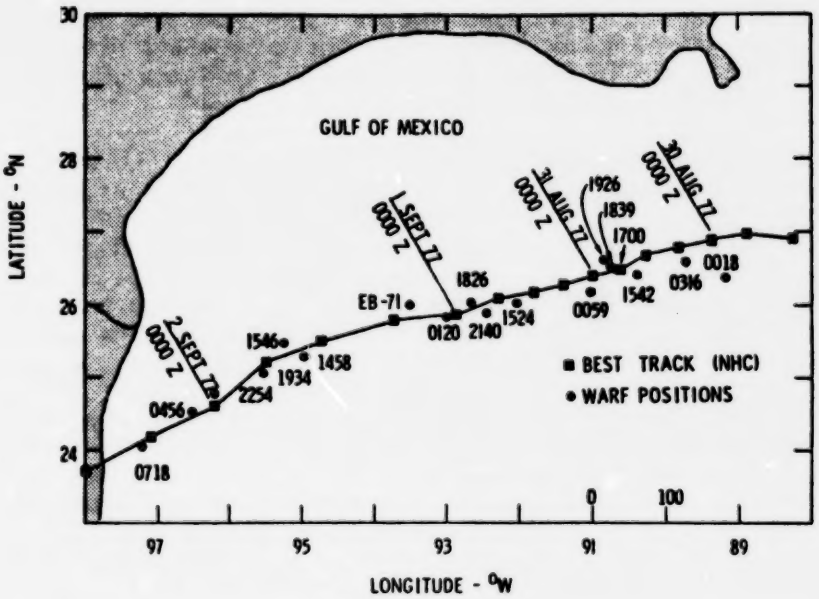


Figure A15. Hurricane track measured by WARF and compared to the National Hurricane Centre's best track. [Courtesy of NOAA]

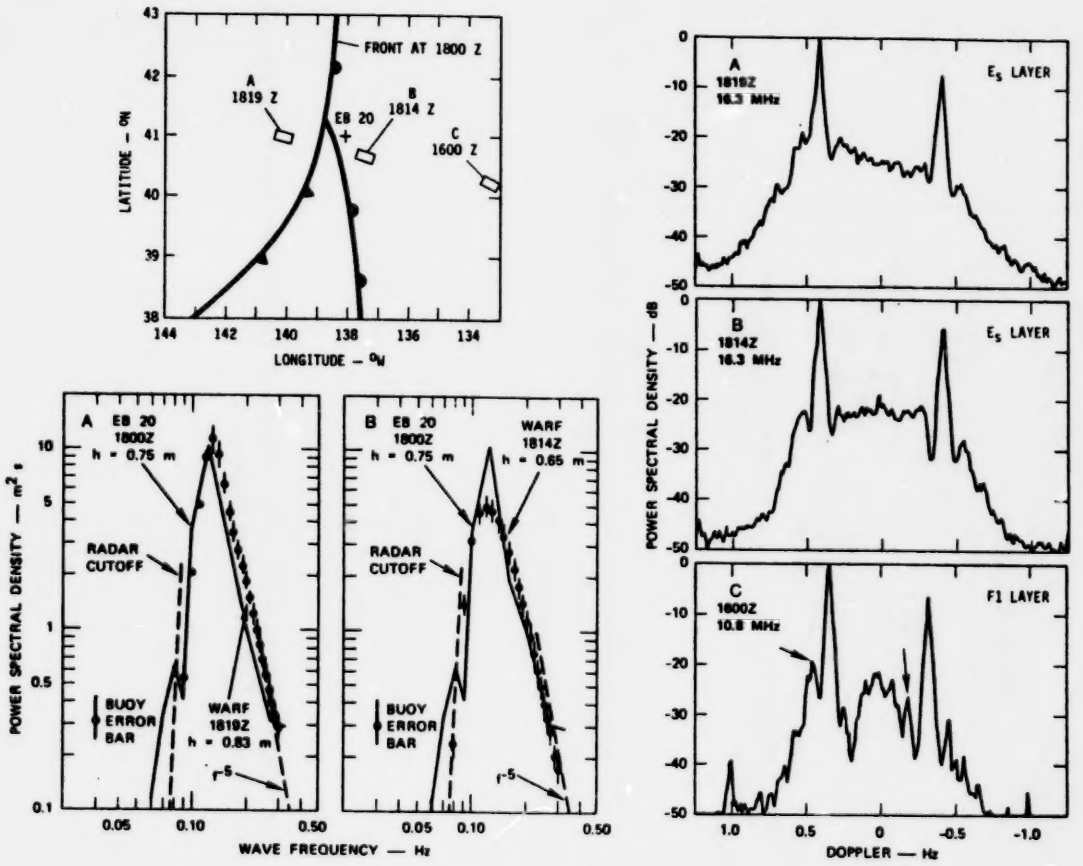


Figure A16. Significant wave height measurements across a cold front.

This spectrum for example was attained at point A which is behind the front which shows relatively high second-order energy compared to the spectrum here ahead of the front which shows a relatively low second-order energy, which is an indication again of the height of the seas. Here is a comparison of the scalar ocean wave spectrum the radar measured, which are the dots, with the one the buoy measured, which are the solid lines. The rms wave height, which is the integration over the whole spectrum, compared very well. The shapes of the spectra compared pretty well too.

This (figure A17) is an example of the real time display of wind direction that we obtained in an experiment that we did a couple of weeks ago out in the North Pacific. This covers the whole radar scan sector. Here's the west coast of North America, Hawaii and a piece of Alaska up here. This is one thing that we can get out in real time: wind direction field. The algorithm messes up a little bit in here and there is some cleaning up that needs to be done. This is just to show you what we can do in real time now by way of mapping wind direction fields.

This (figure A18) is another photograph of a real-time wave-height processor that is actually right off the CRT display that I showed you earlier. This is part of our scheme for measuring rms wave height. The four panels that we have here show the whole Doppler spectrum with some second-order structure clearly visible. This (figure A19) is F2 propagation, and even so, the spectrum is quite clean and quite consistent from time to time. We get one of these pictures every 25 seconds. Even though it's a 100-second integration time to produce these spectra, they are overlapping in time by 75%. We can sit at the radar and watch one of these come on the screen every 25 seconds, and we can wait until we get something we like or until wave-height measurements are consistent. This is just a blow-up of the dominant Bragg line of this spectrum. The current version operating now has some more dashed lines that show the boundary between the first and second-order part of the spectrum that is used in the actual real-time wave height calculation. These things over here are diagnostics that we use to tell how good the quality of the spectrum is. This is the distribution of equivalent width or sharpness of the 84 spectra that go into this average. So if the distribution has a nice shape, we have confidence that there weren't any ionospherically contaminated spectra that went into this average. These two things are time histories of ionospheric things we are interested in. It is broken here in the middle because it is wrapped around. Here is the most recent point right here. This is a time history of the ionospheric Doppler shift which we don't want to change very rapidly, because we know that if it does, the spectra are likely to be contaminated. This is the time history of the average sharpness of this spectrum, which is also a measure of quality. We look for the lowest values of these and if we see the time history going along and its gives us several low values in a row then we tend to have more confidence in the wave-height estimates that are derived from the spectrum. This (figure A20) shows a comparison of significant wave-height measurements made on January 14th, 1981. The current version of the processor that we used a couple of weeks ago also has a real-time display of the

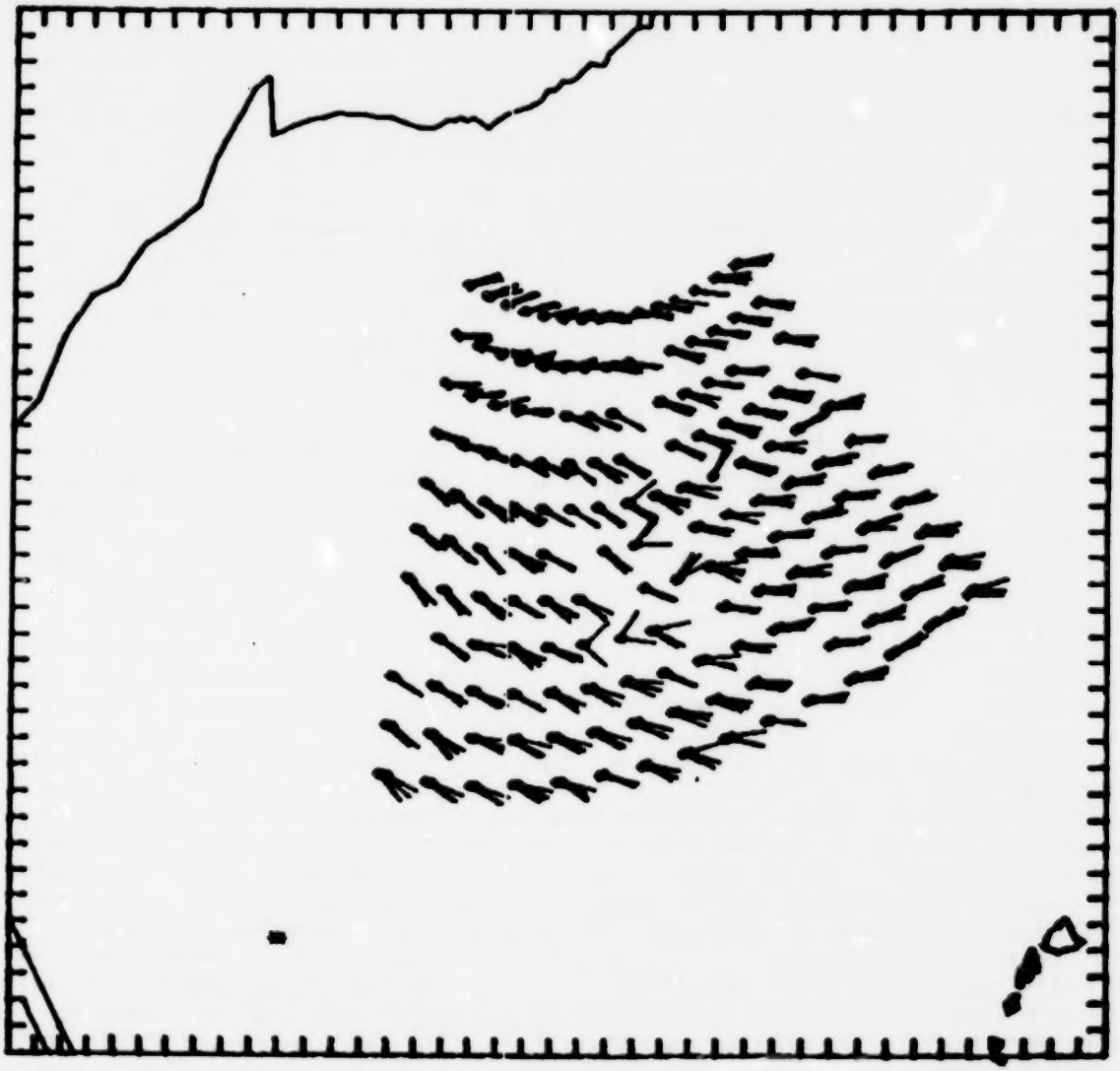


Figure A17. Real-time display of wind direction

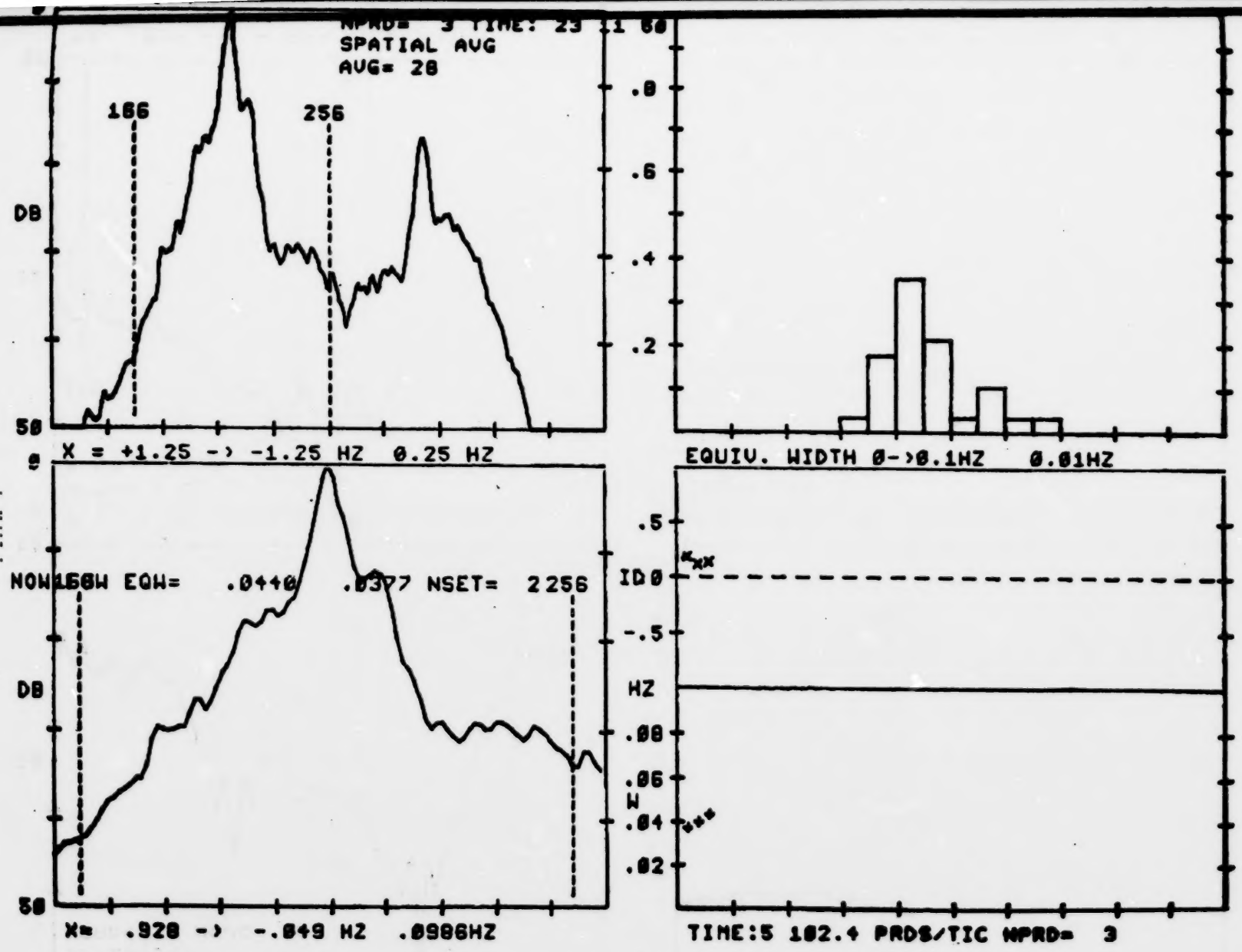
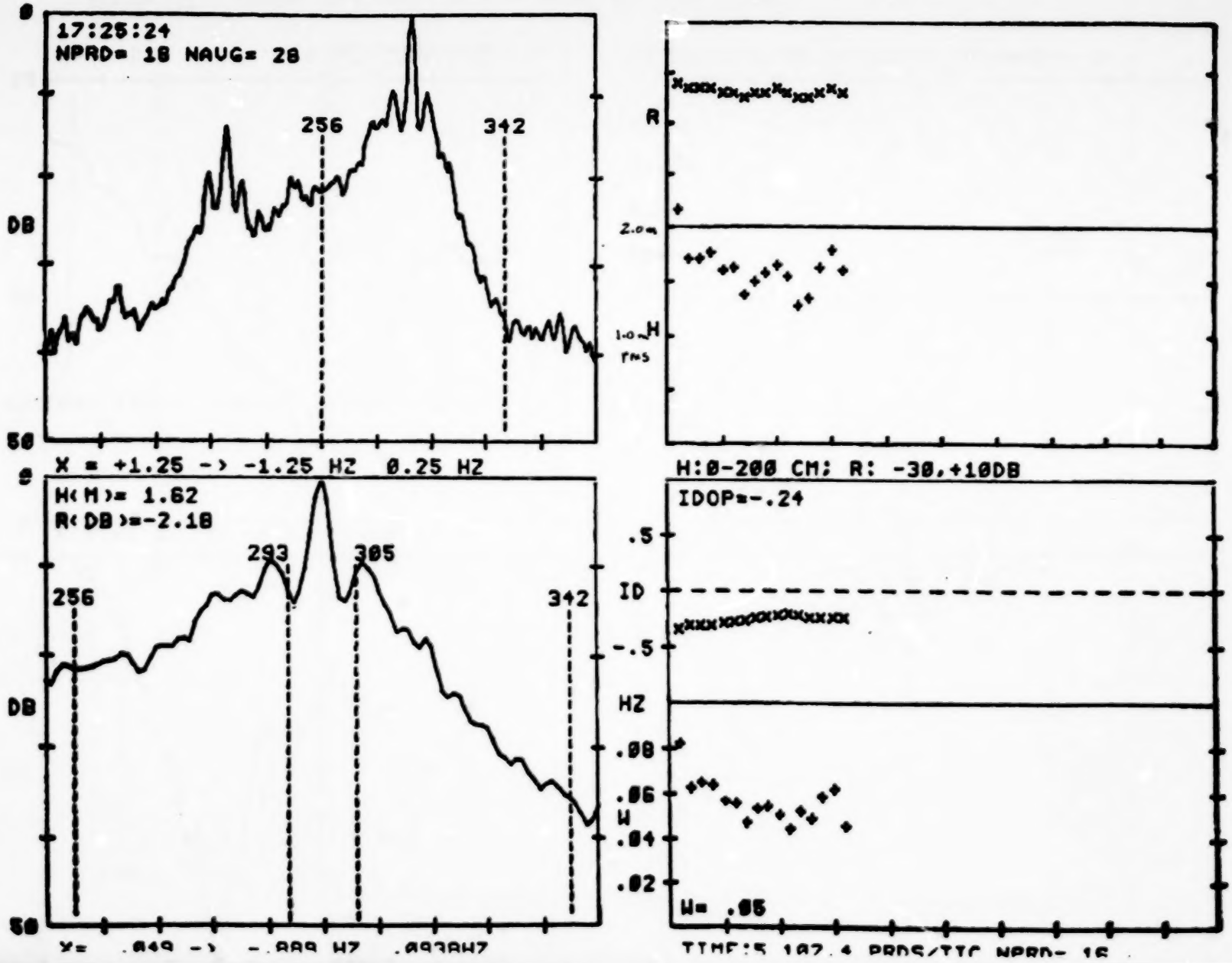


Figure A18. Display from real-time wave height processor at WARF

13 January 1981



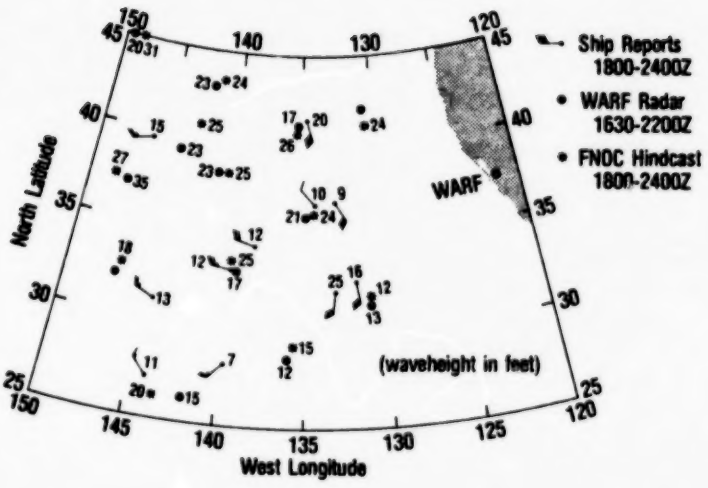


Figure A20 - A comparison of significant waveheight measurement, 14 January, 1981.

wave height as a function of time. So you can sit there and watch the real-time estimates of wave height come out of the processer and decide when you have enough measurements at that cell, then go onto the next cell. Without this kind of real-time feedback your radar is operating blind. I am convinced that you can not efficiently map waveheight with skywave radar without this kind of real time feedback about the data quality. We have tried it and we know that you don't get very far that way. You can sit at a cell for a long time and not get any good data. It is possible to sit at a radar cell and get high quality data very quickly without knowing it and waste a lot of time dwelling at a particular cell that you already have enough good data at. So you really do need this kind of real-time indication of how high the data quality is.

In summary, there is a kind of a hierarchy of things that you can measure with a skywave radar (figure A21). The first and easiest thing is the surface wind direction field. Remember I showed you the wind direction field of a tropical storm, a hurricane. This is a virtually operational capability. It is something that can done in real time right now. It can be telemetered to anybody that wants to pay for it. Surface currents; the feasibility has been demonstrated but with the caveat that you can't do it unless you have a ground reference near by. We don't quite know how far from a ground reference you can measure currents. My feeling right now is that it is a few tens of kilometres. It is not much more than that. Unless you have a zero-Doppler reference such as a shore line, islands, or platforms out there to give you a zero Doppler reference, you can't distinguish the Doppler shifts that are due to currents from those that are due to the ionosphere. The wave or swell dominant period has been demonstrated. That is just the separation of the second-order peak from the first-order peak. Here is an indication of how frequently these things are available in view of ionospheric contamination, just a subjective estimate based on a lot of experience. The rms wave height is the crucial thing and that is what we spend a lot of energy on and I think the success or the failure of a skywave as an operational tool hinges on the rms wave height. We know we can do these things. We are not quite so sure about these things down here. What we have spent a lot of time developing is an rms wave height capability and I think we have demonstrated the feasibility of measuring rms wave height operationally. It takes some patience. It takes being fairly clever about the ionospheric diagnostics and the signal processing. But I think we can do it, and we have demonstrated it. It takes an operational demonstration over an extended period of years to establish whether it is really an established operational capability.

HIERARCHY OF SEA-SURFACE PARAMETERS MEASURABLE WITH SKYWAVE RADAR

		Status	How Frequently Available?
↑ Easiest	• Surface-wind-direction field (e.g., tropical-storm tracking)	virtually operational	virtually always
	• Surface-currents (near shore, islands, platforms only)	feasibility demonstrated	usually
Most Difficult	• Wave/Swell Dominant period	feasibility demonstrated	usually
↓	• Rms wave height (and surface wind speed in hurricanes)	feasibility demonstrated (techniques being refined)	usually
	• Swell direction	feasibility demonstrated	occasionally
	• Scalar wave spectrum	feasibility demonstrated (techniques being refined)	occasionally
	• Directional wave spectrum	under investigation	?

Figure A21

Swell direction has been demonstrated using the second-order structure in a few cases; it remains to be seen how often all the second-order sidebands can be seen to get a swell direction regularly. It has been done several times though, and the feasibility has been demonstrated. Again it's a question of how efficient the coverage is. The scalar ocean wave spectrum has been demonstrated. It's a little bit harder than rms wave height because it requires you to recover more of the structure of the second-order part of the spectrum, so it is much more subject to ionospheric contamination than all the things above it. Remember, this is a hierarchy of increasing difficulty of measurement. The easiest things are on top and the hardest things are on the bottom. The directional wave spectrum is probably way off in the future. It's under investigation but at the moment it seems like the inversion techniques that have to be used to derive the directional wave spectrum are very sensitive to contamination by the ionosphere and at the moment only the most uncontaminated spectra such as those attained from sporadic-E layers in the ionosphere could probably be handled to give directional-spectrum information.

Dr. Barrick

I think that I will try to go very quickly over the last part, I don't want to take too much more time on formal things, so therefore I will cut out a lot of the slides that I have in the last part and just try to give you a flavour of what we're doing now. We started off with a compact system for measuring currents. We talked about that. Tom got into a much larger system, we are involved in, that uses the ionosphere and can look out over large areas of ocean. It therefore has the advantage of obtaining large area coverage but has the disadvantage of being not very transportable and having the ionosphere to contend with. What I will do now is come back to that transportable system again to talk about it for a different application measuring the wave height directional spectrum. It involves the use of a different antenna system. It involves the use of a different part of the echo, the second-order part, which Tom already talked about and I'll just indicate some preliminary results of where we are right now. In terms of a research program we're about three or four years behind where we were with the currents. With currents I think that we can safely say that the system can be operational now. If somebody wants to invest the time then we've got the software developed. The system for measuring the wave height directional spectrum although possible, still requires a year or two of software evolution, before we are ready to say that its operational. I see no obstacles to that right now.

What is a wave height directional spectrum? I guess that is a good question to ask at the start of this, and why does anybody care about a wave height directional spectrum? This is an exaggerated view of one class of user that is worried about the wave climatology in areas they want to work and when they are working in a given area of having a reliable means of measuring the buildup of the wave field around them in order to determine future operations or to evacuate. Just moving one of these semi-submersibles around and anchoring it in a position to account for the wave directionality is a big factor.

Wave height directional spectrum probably doesn't need a lot of explanation to people familiar with Fourier analysis. Basically you can decompose a sea surface into a whole series of waves like this in different directions and different periods. Each one looks very regular. You add them together and you get something that looks like the ocean surface. Because each of these moves in a different direction with its own velocity, because of the unique dispersion relation of the sea, you get a rather random like appearance when they are all added together. Another way of looking at this is waves of different lengths add constructively or destructively just as they do in any field of science and therefore occassionally you can produce a wave at a given location for a brief period of time of extreme height. The study of waves for a given set of statistics exceeding a given height has been a subject of oceanographic study for some time. Again back to the familiar Doppler spectrum where what we looked at for currents and winds and so on are these dominant first-order peaks. What we are looking at now is the second-order structure. It essentially comes from two ocean waves simultaneously interacting. Recall that the first-order comes from Bragg scatter from a single set of ocean waves half the radar wave length. They will be both toward and away from you. This comes from two sets of ocean waves that are interacting. What this shows here is a simplified picture of a radar wave bouncing off one set of waves, bouncing off a second set and then returning to the radar. This is a double radar scatter process. There is also an equal or even stronger process whereby the two sets of ocean waves interact with each other in a non-linear fashion producing a second-order ocean wave from which you then scatter with a single bounce. Both of these are second-order processes. The theory behind them has been well worked out. This is the only equation I want to show but what it shows is a mathematical representation for both first and second-order energy. The first-order as a function of Doppler frequency, ω at a given angle ϕ has those familiar two impulse functions in it. That's the way its represented here. Its the sum over two multiplied by the wave height directional spectrum at half the radar wavelength. Waves are coming towards you and away from you depending on whether n is plus or minus one. The Δ is an impulse function. That's the theoretical expression. To second-order however, those two sets of waves interacting produce a continuum containing the wave height directional spectrum twice (this S is the wave height directional spectrum) and two sets of ocean waves summed or integrated over all sets of interacting ocean waves. This is a quantity you measure as a function of Doppler frequency. This is a known integral equation, non-linear because it contains the wave height directional spectrum twice times what we call a coupling coefficient that is known. It is derived from fundamental electromagnetic and hydrodynamic processes because both the scattering boundary condition and the free water boundary condition at the ocean surface are non-linear. You expand perturbation theory carry it to second-order and this γ is obtained from the second order terms. It is this thing, though that you want to invert in order to get the wave height directional spectrum. The idea is that for first-order, you have only two points on the spectrum. In order to measure the wave directional spectrum at different frequencies you have to vary the radar frequency not over

the upper HF band but down in the MF band which is just totally populated with users. It is impossible. Your AM radio station is right in the middle of it. You'll never get permission to use it, plus the fact that the antenna sizes have to be huge. If you could work with this piece and invert it you've got at one radar frequency, the information necessary to obtain the entire wave directional spectrum. This is what the name of the game has been about for us for several years now, attempting to work with this non-linear thing, linearize it and invert it and demonstrate that the inversion works by comparing it with other data.

O.K. I am going to skip a bunch of this, these are plots of both theoretical and measured Doppler spectra. We first set out to prove that the second-order theory worked by using what is called narrow beam experiment. The narrow beam experiment is like a skywave experiment where you have a huge antenna array form a narrow beam like this and look at a small patch of the sea. We've done that, the results are available now in the literature and I'm going to skip that in my presentation here. They are compared with pitch and roll buoys at three separate experiments and we are convinced therefore that the theory works at upper HF. What I'll talk about though is a more compact system, different from our current measuring system. In this case we use the same radar, the same computer and everything. However we transmit from an omnidirectional element in this case and a different kind of antenna system. We have to use a different kind of antenna system than the four elements because instead of working with that spike we are working with a continuum. The direction finding technique, although it works very nicely for currents doesn't work as far as we can tell for getting the wave height directional spectrum out. So what we end up doing is using this type of antenna system consisting of three elements, a vertical element plus two cross loops. With these we can form a fairly broad beam without moving the antenna just by how we combine the signals from these three antennas. This causes a fairly broad beam to scan a cell in angle, producing an integral where the measured quantity we obtain as a function of scan angle ψ is an integral over angle involving the antenna pattern. For this broad beam system it happens to have this unique nature of cosine^4 type of antenna pattern times the narrow beam sea echo. So this is what we end up working with. The pattern as you recall from electrical engineering from a single loop has this cosine^2 doughnut type shape pattern. This is the pattern say from loop A, the shaded region and from loop B you get a similar one orthogonal to it and because these loops are orthogonal to each other, each of them is capable of receiving this way. The actual antenna looks like this. You combine the signals in such a way that you multiply the signals from the loops by known quantities proportional to the cosine and sine of the angle you wanted to scan to. You then sum the signals and combine it with the signal from the monopole and produce the antenna pattern. Even

though you don't move anything in the antenna system you can effectively in your computer cause this beam to scan to any angle you want or rotate it, and that's the principle of the system.

One way of doing it is to represent the wave height directional spectrum, which is the quantity you want to measure, in a Fourier series in terms of wave number and angle where the Fourier series is over angle. The basic functions being the trig functions in this series. This is a typical representation of what you might expect from it. The mathematics looks like this. This is the broad beam return. This is the antenna pattern that I showed you before. This is the narrow beam return. This is simplified considerably but you put that representation of the ocean wave spectrum in terms of a Fourier series in the expression here for the first-order and the second-order. Everything in here are known coefficients. Because we operate in the upper HF region, we find that it is possible to linearize the nonlinear integral equations to second-order. So this is what you obtain and some of the features of the system we use. As I indicated before all the beam scanning is done in the software. At upper HF the equations reduce, they are linearized nicely but here's the main reason we did it, this system gives identically the same information as a pitch and roll buoy. Right now if you want to measure the wave height directional spectrum the only other technique available is a pitch and roll buoy. A pitch and roll buoy is not operational. It's been around about 25 years. It got started in 1959 and it is not a very reliable technique. Its a mess. Another reason we went into this field is because there is obviously a need and a vacuum in terms of existing techniques. But it does give exactly the same five Fourier coefficients as a pitch and roll buoy. I think I will for the lack of time skip this. All it indicates is as we've gone through attempting to sort out what we get with the loop system we found that we could use the sea echo itself to calibrate most of the problems with a system like this. For example is there a phase difference between the loops? Has the amplitude of one of the loops or monopole gone down because or corrosion? Those are the kind of problems you encounter when you build a structure on the coast and want to operate it reliably for a period of time. You don't want to spend three or four hours a day calibrating your system if there are tests that you can do with the signal in the software. This indicates that it is possible to use the sea echo to calibrate out all the hardware problems that we found will eventually come up and take it out of the data. We started analyzing the data from one experiment we've done so far off California. This is an experiment done in shallow water. I haven't mentioned that before but waves in a dispersion relation in shallow water are different than they are in deep water. As the water gets extremely shallow wave heights deepen and they eventually start to break. Another thing that happens is waves that are going in one direction in deep water start to go in another direction in shallow water so inversion techniques that we have developed that assume you are in deep water and that the wave field is homogeneous

suddenly don't work anymore. But it is possible to correct all that which we did for this particular experiment. This is the loop system we used. Here is a photograph of it on the beach. It is about as tall as I am, so it is fairly compact. These are actually hoolahoops. We were in a hurry to put this together and so we just found two hoolahoops and they were about the right size and strung wires inside of them and put it up. It's a low cost system compared with the one we have now.

This illustrates the wave refraction effect that I indicated. If you have waves of a length like this in deep water and they come towards shore moving into shallower and shallower water they don't come in onto the beach at an angle. They all come in perpendicular but that doesn't mean they were perpendicular further out. It may have been coming at an angle 80° with respect to the coast. You can represent the effective refractive index for water waves just as you can for example an electromagnetic wave in terms of a dielectric. You can represent that whole bending process in terms of refractive index and use Snell's Law which is exactly what we use. Now this assumes linear refraction theory which means that no wave energy is lost due to breaking or anything and that is pretty good up to a point, up to where the water gets really shallow. So you use Snell's law and a dispersion equation for water waves to relate the deep water quantities K and θ to the shallow water quantities that tell you that the wave period gets shorter and that the wave becomes more and more perpendicular to the shore as it comes in. You have to use this in the mathematics. This is a wave refraction diagram showing how waves and contours of equal energy refract and bend as they move into shallow water. What you have to do is use the relationship that the deep water spectrum is equal to the shallow water spectrum, that's not approximation, that's exact assuming no energy dissipation relate the deep water coefficients to the shallow water coefficients. In this particular set of experiments off California we did have homogeneous wave conditions in deep water. In other words it was an onshore wave system which means it is homogeneous in deep water. When it got into shallow water because of that complicated bottom contours, it suddenly isn't homogeneous anymore but the fact that you can use Snell's law in this transformation to get back to deep water indicates that the mathematics is there and you should be able to relate what the radar is observing in shallow water to what it would have been in deep water. You put your buoy out in deep water and if everything works out OK, including your theory, your integral inversion and the shallow to deep water transformation, you ought to get some kind of agreement with the pitch and roll buoy. So cutting a long story short in terms of the mathematics, that's what we did.

This is the alternate system of measurement, a pitch and roll buoy. The waves on this day were about 18 feet high. Fortunately it was California and so I wasn't freezing to death in the water out there. This is another illustration of the fact that when conditions are most interesting for measurement conventional techniques totally break down. We put the buoy

over on that particular day against all best advice. I guess that it had never operated in wave conditions that high and we were told that, this is a Scripps buoy incidently, they would never do it again because of the danger of it flipping over, sinking or smashing into the side in getting it out or getting it back. So another example is that with conventional techniques when conditions are the most interesting you can't make the measurement. With the radar we were sitting back on shore where everything was comfortable and it worked just as well that day. This is a calmer day and this is what the buoy looks like. It is a discus buoy three feet in diameter. Pitch and roll means it has three instruments on it just like the radar antenna. It has inclinometers which sense the instantaneous slope as a function of time in two orthogonal directions and it has an accelerometer which is omnidirectional but measures essentially the vertical acceleration from which through a double integration process you get the wave height. An interesting analogy is that the antenna also has two orthogonal elements that measure like the inclinometers sense wave properties in orthogonal directions plus an omnidirectional element. The analogy should lead you to believe that two will produce the same although the mathematics is considerably different.

These are some results for three different days showing the comparison of the buoy which is the dotted line with the radar retrieved from integral inversion. This is the non-directional part of the spectrum. I'll show that first. It's hard to visually show comparisons of directional spectra one versus another unless you take it in parts. So this is the non-directional part. This axis is wave frequency. This is .05 Hz. This is .1 Hz. This is 10 second waves. That is 20 second waves over at this point. In the Pacific Ocean especially at that particular time there were long waves there, 18, 17 second period waves. This was during a day when the waves were something like 18 ft. significant wave height. As a comparison of radar with buoy you go through all the shallow water corrections, wave refraction, all those effects and take them out. How do they compare when you plot them against the equivalent deep water, non-directional temporal spectrum for the longest most energetic waves? This is the day when the waves were the strongest. These are two other days. This over here is buoy noise but if you take that out these are two other days when the waves were much lower. This was ten feet and this was eight and here the dominant period is about 17 seconds where those peaks occur. Here it's more like 13 to 14 second periods on different days. We have a lot more radar data from that experiment but unfortunately the buoy didn't work for the other days which is a common problem with conventional oceanographic measurements but these are the three days we were able to compare. If you want to measure directional spectrum, how about direction? This is again, as a function of wave frequency in the long wave region the radar direction, a mean direction inferred by integral inversion compared with the buoy. This is 270^{0} which indicates the long waves are coming almost directly out of the west. This is the first day. This is the next day and finally the following day so the agreement between the two instruments is quite good. We spent about an agonizing year trying to figure out what was wrong with the buoy and found that

the compass has been erroneously offset by 60^{o}. We finally got that straightened out and figured out how to correct the buoy also for shallow water. That's not to say that the radar problem was easy, by no means. It took a long time to develop the software, understand refraction effects and take them back out. But to feel that we were comparing an unknown with a known, I think is a bit of an overstatement. The buoy is by no means an operational tool. I spent far more time trying to understand the buoy than I had ever wanted to because what we are out to do is to replace all buoys and drifters and everything else so for some reason I felt that we had to get into the buoy a lot more than we had hoped to.

What do the patterns actually look like? These are the patterns on the one day for three different period waves, 16 second, 13 second, 11 second waves comparison of a buoy with the radar as obtained from the first five coefficients and the agreement as you can see is pretty good. Both produce negative values. That's wrong, a spectrum can never be negative but if you take a Fourier series that has an infinite number of terms and truncate it after five, certainly you are going to produce negative values so there is nothing to be alarmed about. The negative values are always small. These are the fine lines rather than the heavy lines. So I think that what we've proven up to now is that at least in a long wave region, beyond ten seconds for the most energetic region of the spectrum you can invert the second-order part. You can even include complicated effects such as shallow water. Linear wave refraction theory works pretty well and with a loop system which is a fairly broad beam system but compact, you can get good wave directional information in coastal waters.

We recently completed another experiment which a couple of your people came down to off North Carolina and we used a different type of loop system there, a much more efficient one. The first one we threw together was very inefficient, we lost about 20 dB which in terms of system range was about 15 km. That was too much so we built a better antenna system. For those of you interested in hardware, we could talk about the differences in this loop system that make it better. I think it has a lot of advantages but it is still compact. There's another shot of it out over the ocean. It was sitting on top of a dune line about ten feet high next to the ocean. This is another shot looking from the top of the dune line looking up the beach. The big loops are actually sighted by these inner loops and the fact that the entire structure is big copper pipe makes it efficient. The reason it is more efficient is because the input impedance looking into a loop below resonance is very low so you have to build impedance matching transforms and when you do you also transform up the ohmic losses and that makes it inefficient, however you can gain it back by using large copper pipe like this and therefore cut the onmic losses and gain back 23 dB. The vertical part, the omnidirectional part, the monopole, actually is the entire structure fed a slightly different way. That particular experiment is done in much shallower water and what we expect to get from that experiment are conditions where the wave field even in deep water is not homogeneous where we cannot use linear wave refraction theory, so for that set of experiments we intend to develop a new software technique that allows you instead of measuring

a homogeneous equivalent wave spectrum in deep water to actually map the directional spectrum as you move off from shore. It is going to require different formulation of the integral inversion problem. I had a slide showing it but I guess I didn't get it included but that's OK.

One last thing that I will cover is an attempt to stay with compact antennas but do a little bit better at getting angular resolution, I indicated that the reason we use the loops is because it has the same information as the pitch and roll buoy in terms of wave directional information. Well that's fine for initial comparisons but I think that everybody interested in wave directional spectra would like to do a lot better than that because five Fourier coefficients an angle isn't a whole lot. You'd like much better angular resolution. Well the loops are not going to do it. If you use the same loop system for transmit and receive, we only use it to receive right now, you'll buy back some resolution but you really need a better system. We think that we've come up with a circular array technique that uses convolution and deconvolution in contrast with the normal phased array method and it permits somewhat reduced size. In fact it turns out that the antenna pattern from this circular array is independent of size. We've been working on this idea for three years and to me that is like violating conservation of energy to stand up in front of people to make a statement that I can form beamwidth that is independent of antenna size, but I am convinced that it is true. There are some pitfalls with it but at any rate, we've set out to make some measurements demonstrating this. We designed a circular array to use this deconvolution method and prove that in fact we do get an antenna pattern that agrees with theory. This is the structure that we actually built down in North Carolina. It is not exactly your most compact transportable system but we wanted to do it anyway to prove a point. There are eight elements located in a circle here. There is the loop system beside it for comparison. With eight elements you should get about a 45^{0} beamwidth instead of 90^{0} or 100^{0} which you get with the loops. We took some sea echo data as well as data from a boat which was swung around an arc so we hope that we have demonstrated that you get the pattern that you expect. This is a look from the ocean of this same eight element array. It was built such that the structure that I showed you is up high so that the top is even with the dune line. When you look at it from the ocean you see the eight elements as though they are just sitting on the top of the dune. What we hoped to be able to do as we understand sea echo better especially at VHF is to get to the point where we can build a circular array like this of say 16 elements and make it much smaller in size and extend our frequency into the VHF region and really have a compact system. An antenna system like this is needed along with the belief and feeling that the sea echo at VHF behaves the same way that it does at HF which we understand and perturbation theory on which it is all based really works at VHF as well as it does at HF. We haven't quite got to there yet. That is some of the future directions we are aiming at. In other words, more directional antennas and extending the frequency region up as much as we can to produce better estimates of wave directional spectra and currents.

That is where we are now and I guess that summarizes what we all have to say. I am sorry we took so long but I guess all of us wanted to give you a total

picture of what our organizations are doing. I think this summarizes almost all of the HF work and radio oceanography going on in the United States. We have covered some of the work that SRI is doing, Joe Maresca and really that is the state of the art right now. I think that there are two or three other countries, England, France, and Australia getting into the field but we have been working in this field for some fifteen years with an active program for five years and we feel that we have come quite a way. Some of the techniques are operational, some of the theories are proven. In any research program you go along and answer questions and prove things and uncover other questions however that give you further fuel for problems and research. We hope to be able to share with other groups who are interested in getting into the field what we know about it so they can help us with some of the problems and together we can move a lot faster.

Dr. Peters

Well Don that was a very intensive and a very well done two hour lecture. I don't know what the audience feels but I would like to open up the questions no in an informal way and let you deal with the questions yourselves, if that is agreeable to you.

Dr. Barrick

We are going to be around all day today and tomorrow so if anyone wants to get more deeply into math or hardware or whatever by all means we will make plans to do that. But for now we would like to answer any other type of questions. One question that hasn't come up that a lot of people ask is, how much does a system like this cost? We have drawn out various figures for a CODAR type one station system for measuring currents the way I described it. If you would just look at the basic hardware involved, a system like that could be built on the ord of $30,000 - $40,000. It is a bit of a misstatement to say that if you got $30,0 $40,000 to spend you could get an operating system right now for that. Nobody is producing them yet. We still have a little bit of streamlining and optimizing of the software to do. You also have your own investment cost in terms of time and talent to get in and understand it, understand what options the software giv you. It is a tremendously powerful tool, giving you far more data than is available elsewhere but it requires a real commitment on the part of another grou certainly not as much time as we put into it. You need to understand what the system is doing, how it works, the theory behind it, to some extent and convince yourself that your own system is working properly. However, in terms of cost whe you compare $40,000 - $50,000 - $60,000 dollars with conventional oceanographic instrumentation I can tell you right now you won't even touch a pitch-and-roll buoy for less than $150,000 - $200,000. A string of current meters put out in the water and retrieved which gives a currents at maybe two points is going to cost you $50,000 or more. So in terms of cost, the cost for the actual equipment is not that bad. The only pitch-and-roll buoys that I know are for sale right

now are built by a French company and are called a Wadibuoy which costs somewhere around $200,000. There is one available right now if you want to drag it off the bottom down at the experiment we just came from. It didn't make it, along with another pitch-and-roll buoy which is one of the problems that you have with that type of instrumentation. So it isn't that expensive in terms of oceanographic instrumentation when you put it in a total context.

New Speaker

What is your present capability for instance in resolving current speeds?

Dr. Barrick

The best way to describe that is - what is that you want? If you want to measure an instantaneous current and what I mean by an instantaneous surface current is you take a half hour of say 36 minute run of data and then you want to process that as quickly as possible and get a current vector out, I would say that the accuracy right now is between 10 and 15 cm per second. A lot of that is due to the nature of the current you are measuring, the variability of the current over the area that you are looking at. You know the nature of the radar measurement. If you however want to measure surface currents every two hours over a period of 36 hours, extract tidal coefficients and do filtering that 10 or 15 cm per second gets down to about 5 cm per second. If you want to filter some more and get trajectories over a period of a day or two, it's down to one or two cm per second, so it really depends on what you are after. We hoped that we could just throw out a universal number but in a sense it depends on how long you want to average over.

New Speaker

What's your threshold?

Mr. Evans

There is none. The resolution of the system is a mm per sec. The point is how are you going to prove it. A lot of it is done on internal consistency unlike the tidal analysis. If you look at the current like Donald is talking about in a tidal change, you don't see any noise. You have an accuracy problem and you have a resolution problem. If we said it was less than what Don said of 5 to 10 m per second, the first question somebody would ask is how do you know. Well, you can't put anything out the door. There's been some talk of trying to just instrument the living heck out of a one kilometre area which is the cell size by the way, I don't know if that was clear, with electromagnetics or

something like that but even again you are assuming what they see is what's happening on the surface.

Dr. Barrick

We've used three different methods as I indicated in the first part of the talk for comparison. The first is just a spot drifter where you put out a drifter, calculate a mean velocity vector per minute over a period of a half hour and compare it with the closest velocity vector the radar paints for that, one for one. That's the first method. That's how we establish the 10 to 15 cm per second accuracy. Both were done after a half hour data run. The radar may be more accurate than that. The problem is the drifter. If you put two drifters out in the same radar area, the standard deviation between the drifter measurements over a half hour is 10 to 15 cm per second.

New Speaker

That still is not clear. Let me make my question clear. If you have a zero threshold, you can measure currents down to a few millimetres per second.

Mr. Evans

I am limited only in the resolution of the hardware. I am measuring a Doppler shift and the first resolution problem is just a matter if you have X number of points in the time series then what is the resolution in the FFT in the frequency domain which translates to the velocity domain. If you do a very small time series, then your points in the FFT might correspond to 15 cm per second but as you take longer and longer time series, then the resolution gets smaller and smaller.

New Speaker

Its only on your frequency resolution of the system then?

Mr. Evans

Well the hardware frequency resolution is down in the neighbor of a millimetre per second. It's non-existent. It's a matter of how long that time series is that you are willing to take.

Dr. Barrick

We don't believe right now from what we have seen that a definition of surface currents in terms of velocity can ever even come close to what the system

is capable of giving in terms of the actual stability and length of the FFT's. Like he says, it's in the order of millimetres per second. I don't think that it is meaningful to think of currents in that precision. There's no conventional instrument today that will give you that kind of accuracy. When you think of the entire concept of a surface current over an area, the kinds of deviations that we come up with are in the order of three to four cm's per second. So even though you know what your system could measure ten times better than that, I don't think that it is even meaningful to describe surface currents in greater accuracies than that right now until we understand surface currents better. Like I say, take three drifters off and put them in the same area and you get standard deviations between them of 10 to 15 cm per second so what does it mean over the same time period to measure a velocity with a radar to an accuracy of .1 cm per second? I don't know.

Mr. Evans

The other problem you get into is that if your time series gets much longer than about 36 minutes, which just happens to be the size of one of our magnetic tapes, that's where that number keeps coming from, then you have a serious problem that the ocean is not remaining still long enough for you to take that measurement. Things are changing.

Dr. Barrick

That's the big problem. We thought of taking continuous measurements for example over several hours, but three hours is about as long as you can go in a tidal period, probably not even that. An hour to an hour and a half in some of the areas in which we operated and the current is totally different so you are not measuring under homogeneous statistical conditions.

Mr. Evans

There are a lot of games you could play. You could run the radar continuously and then slide windows around and do things like that.

Dr. Barrick

The longest time series we measure is generally 36 minutes. If we measure them every hour then we find that an hour later the currents are different. If you want to measure those differences, then you've got the tradeoff that you can't take the time series too long or you are going to miss some of the detail that you are hoping to observe.

Mr. Evans

We've probably collected in excess of about 9,000 magnetic tapes of data already. This could keep MIT's graduate department going on one weekend's worth of data.

So that's been a real problem. In fact a more severe problem right now is not how to take the data but how to get it effectively analyzed and presented.

Dr. Barrick

One thing that we've developed to facilitate that, is a sort of standardized set of movie software where we can take the data, process it and do movies like you saw earlier. Often times if you are looking for detail or even deciding what's out there that's important to analyse specifically in more detail just looking at a movie of this stuff flash by you very quickly over and over and you suddenly say hey, look at that out there. There's some null zone or dead spot. Let's take the data from that region and really do a detailed analyses of it. We think that by providing a set of movie type software to other people that they would find that useful too as a tool to further study ocean circulation. I think that we need to think as this thing gets used of totally new ways of using and understanding this type of data because it just hasn't been available up to now and I don't know the best way of displaying it or assimilating it into a research program.

Unknown Speaker

Does the cost only involve $30,000 - 40,000? I suppose this is just for the CODAR system?

Dr. Barrick

Yes, for one site.

Unknown Speaker

How about the system for skywave sea state radar?

Dr. Georges

Our latest estimate starting from scratch is 20 million.

Dr. Barrick

This includes buildings and everything.

Mr. Evans

The $30,000 by the way since I am now selling this equipment is a nice estimate for just the hardware for one side. You couldn't get into the business for that right now. If you were in the business and you had no other costs and somebody said go out quick and buy the hardware in volume for one site, it would probably be 20-30 thousand dollars. You are now talking a quarter of a million dollars to effectively get into this type of research project. That is what I've been telling Ken. I'm not trying to discourage him but you have to be realistic.

Dr. Barrick

Where you have two systems built with all the software, you should be thinking in the order of a quarter of a million dollars. If you want to do parts of it yourself, there are variations on that thing, put it together yourself or develop parts of your own software, of course the costs will go down.

Dr. Denner

What happens when you put a big chunk of ice in your field of view?

Mr. Evans

Ken is going to tell us about that in about 12 months, we hope.

Dr. Barrick

Well it depends on how much of the radar cell it occupies. We are thinking in terms of 1.2 x 1.2 km cells. If a chunk of ice in terms of area occupies one tenth of that, it is not going to effect the sea echo much. Your going to see the ice as a large spike near dc. You'll see it. We have never operated in areas yet where we have had ice or expected to see ice. We have only operated in more moderate waters. But this question always comes up. One of the big things that we would probably use a system like this in addition to looking at the surface of the ocean in terms of the scatter from the surface is tracking a transponder. We've built transponders that are triggered by our radar system and then retransmit back at a known Doppler frequency shift. They are coded. You know where

to look for them. They are active devices. They give you a lot more range than the 60-70 km that we get with the actual system. You get up to 100-120 km with the transponder. The electronics package that we have been thinking of for several years is a package that is cheap and therefore expendable. This is feasible for $200 or less for the electronics that would go into a package that you could put on a buoy and let drift or take it out on an airplane and drop it on a floating piece of ice as it drifted past you. You could do a number of things like that.

Mr. Evans

There is a possibility. I don't know what kind of research you get into but we've been contacted by Mobil about the problem of trying to get the mv^2 part of the mv^2 quite accurately in the Hibernia area. We can get down to millimetre per second type velocities but there is a problem with the idea of using transponders and very accurate Doppler radar on ice. The problem is that you need a reference for tracking icebergs. We've been kicking around the reference frame problem. The water is too deep to anchor and you have to have a zero point for inertial navigation which you might be able to do off a platform. You are certainly too far from the coast to use it.

Dr. Barrick

If you really got serious about something like the CODAR, you could ultimately envisage its simultaneous use for several things, for measuring currents by the way I described, for measuring the wave height directional spectrum and for tracking three or four transponders all more or less simultaneously. We've done all of those more or less simultaneously already but not in an operational context. This can all be done at the same frequency. You could be tracking transponders on drifters that are drogued to lower depths for example, so you could get something other than surface currents.

Unknown Speaker

Can you see these transponders in terms of the wave scattered energies?

Dr. Barrick

No. You see the transponder signal as a spike and you particularly pick the Doppler shift of the spike so that it will lie out of the region of the sea echo so it won't contaminate it or anything, and that is very easy to do.

Mr. Evans

You get wave modulation on the signal and therefore get a broadened spectrum back from the transponder depending on what's happened.

Dr. Barrick

You modulate the transponder signal very simply by just chopping it on the transponder at a rate of say 3/4 of a hertz. 3/4 of a hertz is good. That puts it well outside the first and second-order echo region and you can watch that transponder spike sitting there and can track it's velocity and so on very accurately that way. You could track two or three simultaneously, by keeping their Doppler positions shifted so that they don't overlap each other or the sea echo.

Unknown Speaker

Have you ever put this thing in a river and looked at the channel flow?

Dr. Barrick

The most confined area that we put it in is the Puget Sound area where in some directions we only had 3 or 4 kilometres across a channel.

Unknown Speaker

I was thinking of someplace like in a large river, the Columbia for instance.

Mr. Evans

The problem you would have is your spatial resolution which is a reciprocal of your pulse width. With an 8 microsecond pulse width you have about a kilometre resolution. You can cut that down, but as you do it supplies more and more energy with the impulse function in the HF band. Now up here you could probably do whatever you want. You could probably transmit a 100 ns HF pulse.

Dr. Barrick

This is one of the reasons why we are talking about going to VHF. I think that depending on what you want to do, a 1.2 km area resolution may not be very meaningful. If you start to operate in rivers, you'd like to go much finer than

that. In the Columbia River Bar everybody asks you to take your radar and operat it there but they want to see detail of that complicated current and wave feature that is much finer than 1.2 km, maybe 1/4 or 1/10 of that even. I feel that is the only way you can do that is to go up in frequency, therefore your fractional bandwidth involved in a shorter pulse is not that difficult a problem and further more that region of the spectrum is not as densely occupied as it is at HF. That's one of the reasons we're contemplating moving into the VHF region. There are some difficulties involved as I mentioned earlier. What does a sea echo really look like at VHF? How far can you push our use of perturbation theory int the VHF region until everything breaks down?

Unknown Speaker

I would imagine the skin depth too, has quite an effect between the two bands particularly for freshwater areas.

Dr. Barrick

Freshwater does pose another interesting difference. At HF and VHF, the sea for all practical purposes looks like a perfect conductor because of it's salinity. You could replace the whole thing by a sheet of wavy copper for all practical purposes. Freshwater, like a lake or a pond looks totally different. It looks almost like a perfect dielectric and with vertical polarization you get propagation up to 70 km over the ocean because of the good conductivity. You take the same amount of power and the same system over a lake and that propagation of 70 km is going to drop to about 25 or 30. The propagation law for vertical and horizontal polarization over a dielectric is much greater attenuation than over a good conductor like the sea.

Mr. Butt

Don would you comment on the problem that you had in the MARSEN experiment with EM interference.

Dr. Barrick

I think that Mike could talk about that more than I could. I wasn't over there.

Mr. Butt

There are some comments based on some of the work that was going on at CRC and some of the work that Shearman of the Appleton Laboratory Group where they were suggesting that ultimately the best system would be an FMCW system. It would have better capabilities for discriminating in highly congestive areas.

Dr. Barrick

An FMCW system is very effective against interference where the interfering signal coming into your receiver is at a discrete frequency, a very narrow band frequency, for example 3 or 4 kilohertz. If it is narrowband, what happens is in your receiver with an FMCW signal is that you mix with a varied signal that varies over a megahertz or several hundred kilohertz so what it does is it takes that interfering signal which is maybe very strong but very narrowband and makes it very weak but very wideband by spreading it over a large band. If your interfering signal is of that type, it helps you. If your interfering signal is more of an impulsive nature, FMCW doesn't buy a thing.

Mr. Evans

In MARSEN we had some problems with our friends in Leningrad. They have an HF radar and all of a sudden there was a HF radar in their backyard that nobody told them about. There was a game. It was apparently jamming. But we don't know, nobody would ever tell us. There was a problem that as we would change frequencies all of a sudden this broadband source would show up on top of us and Dr. Weber who works for Don, used to have nightmares where we used to see nice clear return and all that we could see for 18 and 20 hours straight was the output receiver just packed right up against the stops of broadband noise. We had these terrible nightmares and the bottom line of the whole thing was it probably raised the noise floor of the radar 1 or 2 dB, but essentially did not affect the data at all.

The system is virtually jam-proof unless you take our pulse rate, regenerate a carrier, lock on to it with a half hertz offset using a cesium or a rubidium standard and sit right on top of us. Now what will take us out is we ramp the gains in the receiver to adjust for the fact that the radar signal is falling off as a function of range. So after we transmit a quarter of a microsecond later we are sitting with this HF receiver wide open and if there is an extremely strong transmitter within the passband of the radar the risk you run is that you just literally overload the RF front end of the receiver. That is the only way that interference really shows up.

In the Gulf of Alaska we apparently had an Auroral scatter. We do real time spectrum in the field. It shows every 30 seconds and we see this interesting little spike that would just kind of wander back and forth in the frequency domain, plus or minus 2 hertz, then go away for awhile and then come back. The only thing we can figure is it was some kind of a Auroral scatter because that particular radar was pointed due north.

Dr. Barrick

But as long as it wanders through your spectrum in a period of a half hour, back and forth, it doesn't bother you. If it sits right there solid

at one frequency right around your first and second-order echo, then you are wiped out.

Mr. Evans

In fact we operate two radars simultaneously offset by about a 100 kilohertz because of the pulse nature of the transmitter through the harmonics from dc to green light. In any given time you can actually see at the other radar site the direct transmit pulse of that radar rocking back and forth. All we do is we just offset the master oscillators of the two radar by a hertz, so that we keep it mov and it never shows up in the data.

Dr. Barrick

Yes, we worried a lot about interference at first, interference between one site and the other, even at offset frequencies where we are transmitting one at 25.4 and the other at 25.8 megahertz. We worried about sidebands or sidelobes of one transmitter going down the throat of the other receiver and so on. When we cleared our phobia of that we then started operating the two at exactly the same frequency and as Mike says found because of the slight differences in stability of the two oscillators, the signals from one tended to drift through the other very nicely.

Mr. Evans

You couldn't stop them if you wanted to.

Dr. Barrick

Even though you see it wander through, the total effect on you is zero and we found other things in terms of interference that never ceases to amaze me. In this last experiment for example, early in the morning at 8 o'clock or so when we'd be operating and the ionosphere is just starting to settle in, even at 25 megahertz, you start to all of a sudden get long distance propagation. We'd sit there with a wideband spectrum analyser and all of a sudden at 25 megahertz, here comes BBC crashing in on us about a quarter to eight right directly down one of our beams from London and in a wideband spectrum analyser there it is just swamping our signal all over the place, but that signal from them is wideband. We then looked at the A scope. The A scope is just a display of total energy and sure enough all you could see is a signal coming in from BBC but when you do the long spectrum analysis over a very narrowband, it's gone. It just isn't there. It never ceases to amaze me.

Mr. Evans

The only strain it really imposes is that you have to have a strong front end on your receiver. You have to be able to take strong interference signals without getting into mods and things like that but other than that it is just classic.

Dr. Barrick

I don't think that we've operated in an experiment that we haven't seen interference at some stage. I don't think that we've ever had to throw out data because of the interference in the final analysis.

Mr. Evans

In the first two years, we would not operate the radar simultaneously because we were scared to. We were always on experiments where some sponsor had our neck on the line. We never wanted to take the chance of what the interference would give us. When we went to Puget Sound we had no choice because we needed the 36 minutes because we were really pushing the maximum range and we needed the signal processing, the averaging but yet if we ran one for 36 and the other for 36 we were in deep trouble in the tidal analysis. So we ran them both at once and it was not a problem.

Dr. Zielinski

What stability are we talking about in your carrier?

Mr. Evans

We're using an oscillator right now that is good to one part in 10^{11}. Its a $600 Austron 1120 L. We had a complete study done on the phase noise requirements of the radar. Its very interesting. They have got about a 10 page paper that shows all the requirements for the radar. The bottom line of the whole thing is that you could probably replace that standard with about a $50 crystal oscillator. We haven't done it yet just because it hasn't been worth it to us to try. It's one of those things you do in steps. I started out where we thought we needed a rubidium standard and it is just not required.

Mr. Butt

Can I ask one more question here at least from my point of view? Some of the communications we've had in the local oceanographic community

here in terms of reservations of this type of system is in the wave-wave interaction. I think that you have demonstrated clearly here in this talk that this is really a second-order phenomenon and does not reflect in the first-order resonant Bragg information if you are looking for current measurements. I know that the CODAR is range limited simply because of range ambiguity due to the PRF. Seventy-two kilometres I believe is the maximum range you can get without getting into range ambiguity but typically most of the literature that I've read shows the range extends in experimental use out to 40 km. Has that lack of range been reflected on the fact that you have had heavy sea state and smearing of the Doppler?

Dr. Barrick

The range is somewhat variable under moderate sea conditions except for the PRF problem that you mentioned which can of course be changed. We calculated right from teh beginning that under moderate seas, say 3 ft seas or 2 ft seas that the range of the system for currents would be about 70 km. I think that that is exactly what we've seen experimentally. There are several variables that change that though. If the wave height goes up you get the sea going from 3 ft to 15 or 20 ft. Boy! You see a big drop in range. It comes down from 70 to 45 and that's predicted by theory. Some 10 or 12 year ago, I did a theoretical study showing what happens to VHF propagation across a rough sea. It effectively changes your effective surface impedance resistance and reactants. When you put that into a surface wave propagation model what it says in effect, is the greater roughness has the effect of a lower conductivity. In other words, you have a more lossy medium, which is very reasonable because the more roughness you have the more energy is being scattered out of the field propagating along the surface so the wave is attenuated more. You see that. On the other hand as the sea gets extremely calm the propagation loss across the sea is fine but the radar scatter from the waves, the radar cross section, goes down and again your range starts to come in. People ask how can you measure currents if there is no waves out there? The answer is you can't. But at the short frequencies we operate at we are looking at 6 m long ocean waves, we've never had a situation in the thousand of hours we've operated even in an enclosed area like Puget Sound, where we didn't have enough energy in that part of the wave spectrum to at least get measurements out to 40 km.

Mr. Evans

Part of the reason I think that we've seen that is that as you go farther out the signal to noise goes down which means you develop better signal processing techniques. I think that when they are publishing

the data in the literature particularly on tidal currents and things like this they are just tending to be conservative right now.

Dr. Barrick

This question really bothered us at first too. How calm does a sea have to be before you don't get scatter from the waves? You do a theoretical calculation but you know you always tend to doubt your own theoretical calculations until you've made the measurements. Theoretical calculations show that a 6 m wave which is what the wave is scattering from to first-order is fully developed when it is 3 or 4 inches high. That's the maximum height that wave can get before instability and breaking starts to occur. If you look out at the ocean and you see any height differences bigger than that then you've got that component of the spectrum there. It's going to give you scatter. As the sea gets calmer then that means that component of the spectrum starts to get weaker and weaker until when it's a perfect flat sheet it is gone. We operated off Florida at times when you could look out of the hotel window and see clouds reflected in the water. It was that calm. All that happened was our system range dropped from about 65 km to about 35 on those days.

Appendix B

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Appendix C

CODAR Technology Inc.

CODAR TECHNOLOGY, INC.

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CTI . . . An Introduction

Codar Technology, Inc. is a problem-solving company specializing in ocean remote-sensing and related technology. We provide engineering design and consulting services for HF radar applications and supply high-quality, reliable systems to government agencies and the petroleum industry. At present, we are providing services to the U.S. Government, West Germany, Canada, and several major oil companies.

Our name is derived from CODAR -- Coastal Ocean Dynamics Radar -- a new ocean remote-sensing tool developed by the Wave Propagation Laboratory of the National Oceanic and Atmospheric Administration. From compact, portable shore stations, CODAR maps surface currents and wave conditions over thousands of square kilometers of sea, providing many times the information available from previous instruments. The response to the CODAR concept from the international oceanographic community has been so enthusiastic that we expect CODAR-derived instruments to revolutionize ocean-surface measurements of currents, wave directional spectra and winds over the next decade.

CTI was formed in 1980 by Michael W. Evans, the co-inventor of CODAR and manager of NOAA's CODAR program since its beginning in 1975. We are developing a commercial market for CODAR-related systems as well as providing research and services in support of their scientific applications. Specific projects now under way include:

- An HF Doppler transponder system for accurately tracking the velocity of ice and ocean currents.
- Second generation CODAR systems in support of U.S. and foreign research programs.
- Extension of CODAR measurement capabilities to include directional ocean-wave spectra.
- Development of a CODAR system for use on offshore oil production platforms.
- Data acquisition systems in support of the petroleum industry and government research programs.

Recognizing that few ocean remote-sensing problems can be solved within the confines of a single discipline, CTI has assembled a unique cross-disciplinary team of consultants and senior staff with expertise in the following areas:

- Radar systems engineering
- Digital/analog signal processing
- Digital hardware/software engineering
- Mathematical theory of radar interaction with the sea
- Data analysis and interpretation
- Field engineering
- Oceanography

To meet short-term customer requirements efficiently, CTI utilizes outside contractors and consultants, who provide research, design and manufacturing services on a demand basis. We also maintain well-equipped engineering and computer facilities. Please contact Codar Technology with your ocean remote-sensing problems.

APPENDIX D

Funding for CODAR Current Mapping System

FUNDING FOR CODAR CURRENT MAPPING SYSTEMS

Program cost falls into the two distinct categories of equipment acquisition and development phase.

C-CORE's original proposal to Supply and Services Canada (DSS) deliberately emphasized this separation with the plan of generating a dual funding program where government would support development and industry would acquire the equipment.

Although, an implementation has taken longer than expected, this scheme has been achieved at least in part with government, while industry, through the Arctic and Eastern Petroleum Operators Associations (APOA and EPOA), is indicating support. A special meeting of the group is planned on May 19th, 1981 to hear our presentation on the subject. CANMAR Ltd. is showing interest in the surface current program as it may relate to their drilling operations in the Beaufort Sea while Mobil Oil Canada, Ltd. are interested in East Coast applications.

All of the hardware for a CODAR current mapping system is commercially available and some components such as the transmit/receive antennas, the antenna multiplexer and VHF data link can be assembled in house. All of the computer equipment can be purchased in Canada with exception of the Signal Processing Interface (SPI). Due to very limited demand for both the SPI and HF receiver they are at present only available from a single supplier in Boulder. Colorado. Hopefully as the technology transfer nears completion the Canadian radio electronics industry will be in a position to respond to future developments. An item of particular importance will be the opportunity to direct the development towards specific problems that are unique to Canadian waters.

One CODAR radar site will be purchased in any event for C-CORE's ice radar research program in order to prevent delay. Major processing hardware for one site has beem supplied for the project through Supply and Services, Canada (DSS) bridge funding to Fisheries and Oceans. If the emphasis remains on the current mapping function, then additional computer hardware will be required. Meanwhile existing equipment is also finding application to processing the data runs for C-CORE's skywave radar project (Butt et.al., 1981) with the Communications Research Centre in Ottawa.

An estimate of the funds required for the full development program are summarized as follows:

	to March 1982	to March 1983
Labour -	$ 79,300.00	$ 63,300.00
Materials -	9,400.00	6,900.00
Subcontracts-	10,700.00	4,800.00
Direct Costs-	12,200.00	55,500.00
Travel and living -	7,800.00	6,900.00
Overheads -	24,900.00	19,600.00
	$144,300.00	$157,000.00

Total development costs are $301,300.00

The following is a detailed cost component breakdown for a complete "one site" CODAR system including the VHF data telemetry link and access to NOAA software.

1	PDP 11/23 minicomputer system	$36,100
1	SPI board (CODAR Tech. Inc. (C.T.I.))	6,000
1	Video interface board (C.T.I.) and display	3,600
1	CODAR (non-volatile) memory (C.T.I.)	1,200
1	Filter/crystal set (C.T.I.)	1,920
1	HF receiver (C.T.I.)	35,000
1	HF transmitter (10 kw)	12,000
1	VHF telemetry system	12,000
1	Transmitting antennas (HF)	2,360
1	Receiving antennas and multiplexer (HF)	4,200
4	ECS containers	8,000
1	CODAR transponder	3,600
1	CODAR software package	30,000
		$155,980

Note that U.S. prices in the above cost breakdown have been prorated to Canadian dollars based on a 20% exchange rate, miscellaneous costs are included under the related item listings and FST, Duty and Provincial sales tax have been excluded.

Acquisition of this equipment by industry and applied in combination with the hardware acquired for C-CORE's ice radar research program would complete the two site CODAR system needed for "full vector" surface current mapping. A summary of the cost sharing program is shown in the attached figure.

CODAR

INDUSTRY

CAPITAL EQUIPMENT EXPENDITURE
- ONE RADAR 'SITE' (½ CODAR)
- ONE TELEMETRY LINK
- PURCHASE OF SOFTWARE RIGHTS

160 000

C-CORE
SPONSORED PROGRAM

CAPITAL EQUIPMENT EXPENDITURE
- ONE RADAR SITE (½ CODAR)

120 000

GOVERNMENT (DFO)

MANPOWER & IMPLEMENTATION COSTS

300 000

OPERATIONAL CODAR SYSTEM PLUS TRAINED PERSONNEL

Limited availability mid 1982
Demand availability mid 1983

COASTAL ZONE MAPPING FOR EIS SCENARIO PREPARATION

Three month rent free provision for industry

CONTRACT OPERATION, MAINTENANCE AND RENTAL MANAGEMENT BY C-CORE TRAINED PRIVATE CONSULTANT

DEMAND AVAILABILITY FOR CONTRACTUAL APPLICATIONS

RESEARCH APPLICATIONS (C-CORE)

- ice hazard radar
- Iceberg Tracking
- etc.